United States Geological Survey
Award No. 03HQGR0022

EXOGENOUS UNCERTAINTIES IN EARTHQUAKE RISK MODELING FOR INFRASTRUCTURE SYSTEMS: A DEMONSTRATION EVALUATION IN NORTHERN CALIFORNIA

Dr. Craig Taylor
Natural Hazards Management Inc.
5402 Via Del Valle
Torrance, CA 90505
310-791-0043(ph); 310-791-6684(fax)
cetaylor@earthlink.net

Mr. Stuart Werner
Seismic Systems and Engineering Consultants
8601 Skyline Blvd.
Oakland, CA 94611-1635
510-531-7489(ph); 510-531-7293(fax)
sdwerner@ix.netcom.com

Dr. Walter Silva
Pacific Engineering and Analysis
311 Pomona Avenue
El Cerrito, CA 94530
510-528-2821(ph); 510-528-2135(fax)
pacificengineering@juno.com

Dr. Mark Aschheim
Department of Civil Engineering
University of Santa Clara
500 El Camino Real
Santa Clara, CA 95053-1500
408-554-6871(ph); 408-554-5474(fax)
maschheim@scu.edu

Mr. Larry Scheibel
Senior Project Engineer
Geomatrix Consultants
2101 Webster Street, 12th Floor
Oakland, CA 94612
510-663-4100(ph); 510-663-4141(fax)
lscheibel@geomatrix.com

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INTRODUCTION

1.1 CONTEXT AND OBJECTIVES

1.1.1 Context and Criteria Within a Broader Decision Context

Those concerned with practical applications of earthquake data often use hazard-related metrics that are associated with seismic building codes and other seismic design and redesign practices. These metrics consider, for instance, probabilistic earthquake ground motions in terms of a non-exceedance probability of X% for an exposure of Y years (e.g., 10 percent probability of non-exceedance in 50 years). However, as performance-based earthquake engineering has demonstrated, the suitable metrics for evaluating building code measures and lifeline system and component performance requirements should instead be risk-related. These translate physical outputs into such decision-related outputs as expected dollar losses relative to costs of undertaking specific seismic measures. For lifelines systems, as examples, the dollar losses include not only expected repair costs for components but component downtimes, resulting outages, and their general implications for lifelines systems owners and operators and for the public at large.

Concern for the role of uncertainty in earthquake lifelines decision-making has become more intense as complex simulation programs have developed to assess earthquake hazards and risks and as the many dimensions of earthquake lifeline decision-making have become clarified. Complex simulation programs permit hazard and risk results to be produced with a fair degree of comprehension and the appearance of precision. At face value, such programs suggest that one could turn lifeline earthquake decision-making into decisions under risk, decisions for which all pertinent dimensions are quantified with precision. (See M. Resnick, 1987, for the distinction between decisions under uncertainty and decisions under risk.)

Yet, this goal of providing such precise hazard and risk information is challenged because of the many dimensions of lifeline earthquake risk decision-making, and the very significant uncertainties that are *ex hypothesi* not comprehended in complex simulation programs.

The many dimensions of lifeline earthquake risk decision-making include political, social, ethical, administrative, and a host of other considerations that are typically not comprehended in complex simulation programs. It is well-known that it is difficult to quantify, for instance, all "costs" of disasters and similar remarks apply to opportunities and challenges for those who are not victims of disasters. (See The H. John Heinz III Center for Science, Economics and the Environment, 2000) In a series of Earthquake Engineering Research Institute lectures, W. Petak (ATC-58 presentation, 2/24/03) has maintained that seismic risk results and their uses are dependent on a variety of contexts. One might add that one cannot comprehensively explicate all contextual factors.

Hence, the quantitative criteria for evaluating diverse models and sub-models require consideration of a much broader decision context than is conventionally explored. For some time, especially before the popularization of performance-based earthquake engineering, seismic hazard criteria have been used to evaluate the applications of geoscience models and sub-models. In this report, risk rather than hazard criteria will be used to evaluate the applications of these models.

1.1.2 Closed and Open Modeling Systems and Endogenous and Exogenous Uncertainties

Complex simulation programs for evaluating seismic risks involve many models and sub-models. The estimates made would be part of *closed systems* if all uncertainties were fully accounted for. Error terms in these closed systems purport to capture completely all uncertainties that could impact estimates of seismic risk. The hypothesis in this report, however, is that these complex simulation programs are *open systems*, systems whose models and sub-models typically can admit considerable improvements, including in some instances overall replacements for some of the models and sub-models. Moreover, only some uncertainties are typically considered in such complex seismic risk models. (For a generalization of the theme that important risk evaluations require open systems, see Apostolakis, 2004.)

The expression "*endogenous uncertainties*" is used in this report to denote *those uncertainties as modeled* in complex simulation (seismic risk) procedures. To be sure, some seismic risk procedures may not in fact model any such uncertainties. These procedures may treat locations of earthquake sources, attenuation, amplification, component response, and system response deterministically. Or, probabilities can be attached to each earthquake source in such procedures. Other seismic risk procedures may model some more or less greater sets of endogeous uncertainties. In contrast, the expression "*exogenous uncertainties*" is here taken to denote *those uncertainties not typically modeled* in complex simulation (seismic risk) procedures. In this context, it is clear that so-called aleatory and epistemic uncertainties may be, dependent on circumstance, endogeous or exogenous. The focus of this report is on exploring typically exogenous uncertainties.

1.1.3 Report Objectives

The objectives of this report are two-fold. First, through clarification of the decision context and the role of hazard and risk information in this context, this report clarifies how hazard and other information fits into lifeline earthquake decision-making. Not infrequently, quantifiable factors that have not been investigated in depth turn out to be dominant or at least major, such as the real discount rate used in investment decisions (see Ferrito et al., 1999). Second, the report provides results of evaluations of the effects of exogenous source and site uncertainties on the seismic performance of a wide range of simple inelastic structures representative of many types of lifeline components (short bridges, wharves subjected to ground shaking, buildings that house key equipment for lifeline system operations and administrative/engineering functions, etc.). Finally, this report explores the issue of uncertainties and of the degree to which lifeline earthquake risk reduction decisions are both decisions under both uncertainty and risk. Decisions under uncertainty may be conceived of as being similar to decisions in which one is asked to bet on the color of a ball in an urn (e.g., "green") when one does not know if any of the balls in the urn are this color. To what extent, then, are lifeline earthquake decisions under uncertainty as well as decisions under risk? To what extent are lifeline earthquake decisions subject to outcomes that result from open as opposed to closed quantification procedures?

1.2 BACKGROUND

1.2.1 The Decision Setting.

When alternative seismic risk reduction measures are being considered by decision-makers, these may be viewed in terms of the flow-chart developed by the American Lifelines Alliance (ALA) (see Fig.1-1). The highlighted boxes refer to major elements of the simulation process for a complex or composite model: inventory development, hazard identification and analysis, component vulnerability evaluation, and system vulnerability evaluation (which may also include macroeconomic evaluation of higher order losses). The highlighted boxes also correspond to the analytic portions of this report.

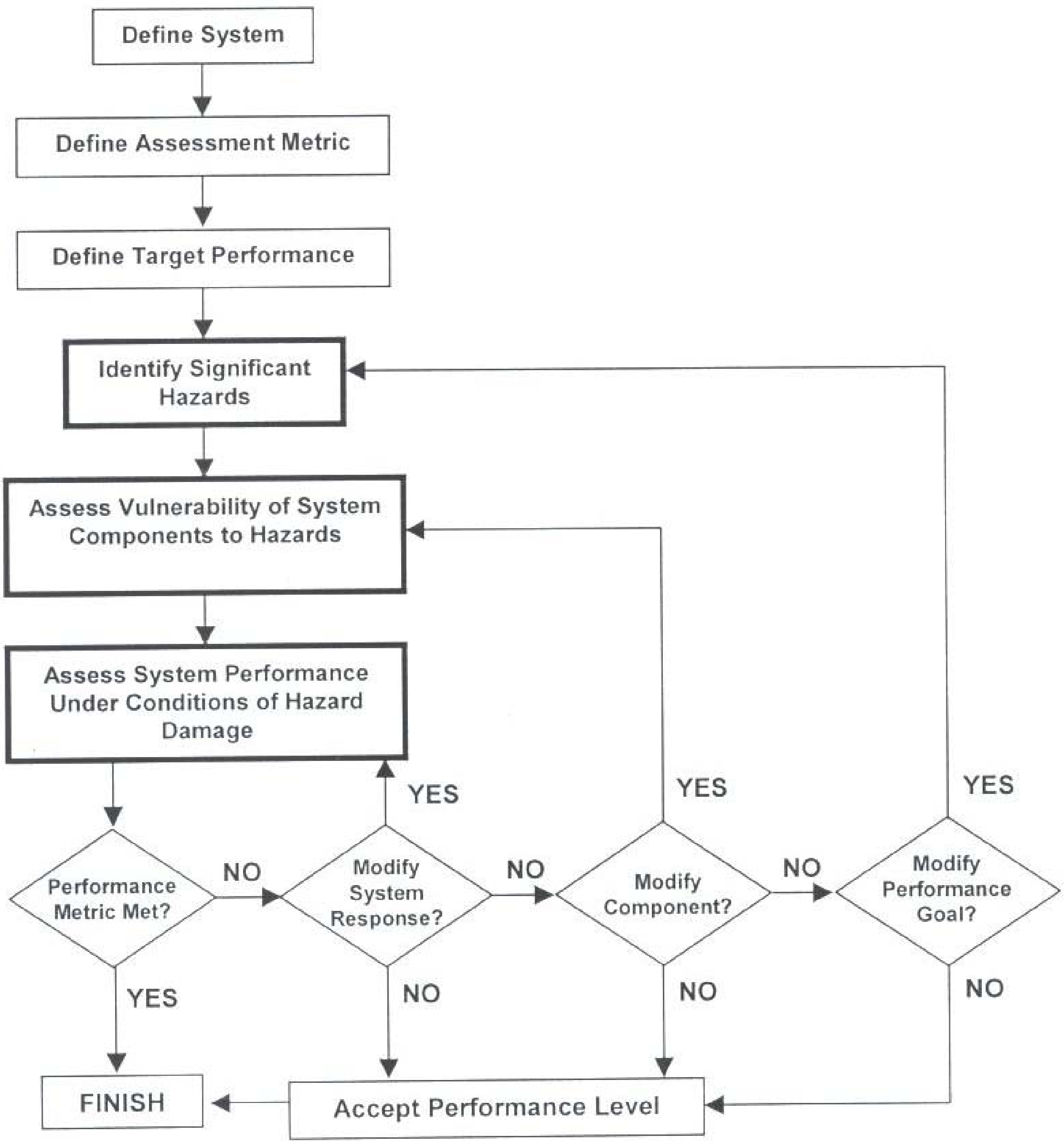


Figure 1-1. Risk and Decision Procedures (ALA, 2004)

The non-highlighted boxes in Figure 1-1 refer to how the overall decision process incorporates the results of this simulation process. These results could be extremely variable. Many practitioners are preoccupied with results of Probabilistic Seismic Hazard Evaluations (PHSA's), which in the simulation process envisioned in this study can yield intermediate outputs. These intermediate outputs have often been used in new seismic design and other decision processes which of course ignore uncertainty in other elements in the simulation process envisioned in Figure 1-1. Other outputs of this simulation process can include average annualized losses, their variance, and their coefficient of skewness. These can be used in various decision processes requiring consideration of costs and benefits of alternatives under consideration by decision-makers. For over fifty years, and especially for the past two decades, non-federal entities including capital markets have paid special attention to elements of the investment decision (costs and benefits, or yields on investments) beyond the mean outcomes and including especially the statistical variance (the mean-variance criterion for portfolio investments) but also the entire distribution of outcomes (see Markowitz, 1959, Levy and Sarnat, 1984, Daykin et al., 1994, Bernstein, 1995, Levy, 1998, Alesch et al., 2002).

The non-highlighted boxes in Figure 1-1 also permit decision-makers to entertain considerations beyond those derived through a thorough simulation process--which typically stresses technical, economic, and financial considerations. For instance, decision-makers may also have budgetary, legal, political, social (equity), aesthetic, and other considerations that may in some cases be dominant in the decision at hand. (Petak, 2003)

1.2.2 The Complex or Composite Statistical Model

The simulation process envisioned in Figure 1-1 consists of the application of a complex or composite statistical model consisting of potentially many sub-models (including modules), input data, assumptions, and simplifications. These sub-models, input data, assumptions, and simplifications must fit together to produce desired intermediate and final outputs. There are many instances of this need to integrate pieces into a composite model. For instance, a module containing one attenuation model may require that the overall simulation calculate "distance to source" in the same way as intended in the attenuation model. For another instance, the definition of intensity used to construct a component vulnerability model must correspond to the intensities calculated in the seismic hazard model. For a third instance, locations of system components must be translated into a consistent geographic reference system so that hazard calculations for sites and sites as defined in the systems evaluation are consistent.

Within this composite simulation program, calculations can be made that yield explicit distribution function results of the endogenous uncertainties. For example, the authors have published a "walkthrough" or raw Monte Carlo approach to evaluating the earthquake risks to roadway systems (in a program entitled REDARS). (See Taylor et al., 2001; Werner et al., 2000) In this time-series Monte Carlo approach, "year-samples" can be produced for earthquakes (with no damaging earthquakes in most years for a specific lifeline system). Each year-sample constitutes an independent trial. As a result, Bernoulli processes can be used to define confidence limits for such simulation outputs as average annualized loss and various fractile estimates (e.g., the 500-year loss). For instance, a 50,000 year-sample for the Shelby

County, Tennessee roadway network -- which contained about 780 earthquakes that caused some economic loss due to travel time delays -- yielded economic loss results with a 95th centile confidence that the true value of the losses due to travel time delays will be within of about +/- 12% of the average annualized value of these losses. More recently, we have supplemented these Bernoulli processes with variance reduction techniques in order to reduce the number of simulations needed to achieve the same confidence limit. Investigations have found that these variance reduction techniques require only a slightly under 16,000 year-sample, or about 230 events with travel-time losses, to achieve same confidence levels and limits that were obtained before by considering 780 earthquake events. (See Perkins and Taylor, 2003; Taylor et al., 2004; Bradley and Tibshirani, 1993)

As will be shown in this report, these same Monte Carlo procedures can be applied to such intermediate outputs as strong ground motion hazards in order to estimate confidence levels and limits of various fractile estimates for strong ground motions (e.g., the 475 year estimate). In this sense, these procedures are strongly consistent with probabilistic ground motion hazard analysis. Results should be statistically identical given the same source zones and strong ground motion attenuation functions. At the same time, the "walkthrough" procedures in this report emphasize the capacity to simulate random walks of various exposure periods as well as considering spatial variabilities and spatial correlation in target lifeline components. In decision-making, different planning periods (e.g., 5 years for some insurers and reinsurers, 30-years for some lifelines managers and operators) can be of critical importance. Various pre-sampling techniques such as Latin squares (or hypercube) modeling or "exhaustive/numerical" modeling that provide some additional efficiencies in deriving strong motion fractile estimates at the expense of losing the capacity to examine a long annual time-series in order to obtain the variability of loss for specific exposure periods.

1.2.3 <u>Endogenous Uncertainties</u>

As defined previously, endogenous uncertainties are those uncertainties typically modeled in probabilistic strong ground motion hazard analysis and loss studies. These could include the uncertainties modeled locations of earthquake sources, earthquake magnitudes, rates of occurrence of earthquakes associated with specific fault traces and/or areal sources, source-to-site attenuation through hard rock, site dynamic amplification, the physical response of a system component to input strong ground motions, local ground displacements, the associated downtime for various system components (e.g., bridge structures, high-voltage electric power substations), and the response of the system to single or multiple component failures.

Consideration of endogenous uncertainties has been shown to have fruitful results in recent inquiries employing "tornado diagrams." (see Porter et al., 2002) In such a study, one determines the value for loss given each parameter at a nominal value and a high and low fractile value, the other parameters remaining the same. A graphical diagram is produced showing the range of loss results stacked from highest to lowest impact, and having a "tornado" shape. If a parameter makes a significant difference, then a focus should be on estimating this parameter more precisely. If not, then the parameter may be fairly safely ignored in subsequent inquiry. As the distinction between endogenous and exogenous uncertainties is worked out fully, statistically very minor modifications in a baseline model as a result of including or excluding uncertainties in sub-models or parameters will be considered as being chiefly endogenous (written comm., K. Porter, 1/03). In the study cited, "assembly capacity," a response feature of the structure not usually subject to uncertainty study, and hence exogenous, is found to dominate the uncertainty owing to ground motion attenuation uncertainty, almost always endogenous.

In principle, if one were to include at least some of the most important endogenous uncertainties in a seismic risk procedure, one could evaluate enough simulations (year-samples or samples for some fix duration) to create extremely precise or virtually exact estimates of losses. However, the systems evaluation methods are so time-intensive that more realistic "nominal" confidence limits must suffice in practical contexts. Practical constraints are thus the primary limitation on the precision of seismic risk estimates that incorporate endogenous uncertainties. If seismic risk procedures were closed systems, then accuracy would be a function of how many simulations were evaluated.

1.2.4 Exogenous Uncertainties

Exogenous uncertainties, in contrast, are those typically not explicitly modeled in the complex simulation process. There are several reasons why various practitioners have maintained that there are uncertainties beyond endogenous uncertainties (Trifunac, oral. comm, 2000; Perkins, 2002). Three such reasons here are (a) there are economic needs for simplifications within complex simulation programs, that is, "models" in this context are used in order to provide practical means to achieving forecasts, not because they comprehend reality completely, (b) alternative models arise along with new data or reinterpretations of older data, and (c) validation of composite models is often very challenging, with an emphasis on validating sub-models in view of these scarcity of data in comparing actual events with random outcomes (with prospective distributions). (See for instance Rose, 2002, on challenges in validating higher-order economic loss models.)

The economy of efforts in constructing and maintaining complex simulation programs is a key factor in understanding them. Basically speaking, these complex simulation programs are instrumental. They are not designed for solving all problems or dealing with any set of issues but are instead designed for specific purposes (and may be adapted to a variety of other purposes). Their systematization extends only so far as they serve as tools in various research and decision contexts.

Reasons (a) and (b) above illustrate that complex simulation programs deal in the first place with models (and sub-models). Incorporating all pertinent parameters and sub-models and qualifying all pertinent data is unlikely for complex models. Systematic errors are therefore relatively likely, and future inquiry and experience may uncover these systematic errors. Likewise, for the purposes for which a composite model is designed, more detailed evaluations of sites, components, ground motions, system characteristics, and other somewhat relevant elements may not be economic. Simplified models may suffice for purposes intended or at least within economic constraints (on time, computer capacity, priorities, and so on).

The validation process for pertinent composite models indicates further how those undertaking validations may face scarce and complex data for validating the models as a whole:

- Results of actual earthquakes may be used in this validation process. Selected data may exist for strong ground motions at specific sites. These data may be extrapolated and interpolated to other sites—with a very large error term.

- Similar remarks obtain to estimates of component damage.

- Estimates of functionality may in some cases be initially subjective, and subject to variabilities in inspector judgments.

- Estimates of repair cost may depend on bidding processes, bonus incentives, and the like. Hence, institutional, psychological and other human factors may enter into these estimates, along with physical random elements.

- Estimates of system losses may further encounter many variabilities. These pertain to how resilient system operators with variable outside assistance are in restoring service.

- Macroeconomic losses may encounter all these challenges along with challenges of taking into account other damages in the affected region that may impact on overall regional losses.

- Attribution of regional losses to losses in a specific system may likewise involve assumptions and conjectures.

In the end, one may have a single scenario with say one estimate of system loss that is itself the result of random processes, and one may have a single estimate of macroeconomic losses as a consequent of this system loss. These two data points may constitute some point on the possible distribution that the composite model with all explicit uncertainties modeled would yield. So, it would be dubious to reject the composite model based on such a data point, which, however, may constitute an outlier (an extreme on the distribution) in a random process. Of course, one data point (or a few data points for a few scenarios) do not constitute a very robust validation process. Accordingly, the focus of validation procedures for such composite models has been on the sub-models and assumptions -- which is still a daunting task.

1.2.5 Comparison with Aleatory and Epistemic Uncertainties

In this context, the expressions “endogeous uncertainties” and “exogenous uncertainties” may be confounded with the distinctions between “aleatory” uncertainty and “epistemic” uncertainty that has become familiar in professional circles. Based on three sources (Toro et al., 1997, EERI, 2000, Panel on Seismic Hazards, 1996), there is some consensus that

- Aleatory (random) uncertainties are those that cannot be reduced through further inquiry (experimentation, experience, analysis).

- Epistemic uncertainties are those that can be reduced through further inquiry

Note that the endogenous uncertainties in a seismic risk procedure may include both random uncertainties and uncertainties that can be reduced through further inquiry. For instance, a specific uncertainty evaluation for a model or parameter may include a presumed distribution when, in fact, the underlying uncertainty distribution is unknown. The use of parametric models itself potentially permits the substitution of non-parametric procedures that do not impose specific assumptions about the form of the distribution in question. Such data-driven or non-parametric procedures may provide superior specifications of the uncertainties in question. In addition, endogenous uncertainties may be uncertainties both with respect to the central values and the scatter about these central values.

Note also that some random uncertainties may not be modeled in a seismic risk procedure. Some seismic risk procedures model few if any uncertainties. Hence, to the extent that such terms are understandable, the expressions "aleatory uncertainty" and "epistemic uncertainty" do not comprehend what is at issue in this report.

SECTION 2.0
APPROACH

2.1 BASIC APPROACH

The basic approach to this exploration of uncertainties in lifelines seismic decision making is to (1) develop a composite lifeline seismic risk model that is the baseline model (2) explore endogenous uncertainties in this composite model and (3) explore the inclusion of alternative (exogenous) models, data, or assumptions and their effects on decision-related outcomes.

2.2 THE BASELINE MODEL

2.2.1 Simplified Regional Model of Berths

The baseline model primarily provides a simplified systems evaluation for a hypothetical regional port system consisting of four main sites (one on the shores of San Francisco, one on the shores of Richmond, CA, and two on the shores of Oakland. Each site has a wharf capable of serving one ship at any given time. Each berth has a replacement cost of $40M. Two ships are docked at any given time.

It would take a long exposition to outline all the simplifications in this systems model. Ships are undifferentiated by size. Cranes, backland storage areas, shipping schedules and potential queues, rail and trucking systems, tenant leases, longshoreman contracts and hours, and a host of other considerations are omitted from this simplified systems model.

2.2.2 Basic Earthquake Occurrence Model

The baseline earthquake occurrence model is derived from the four U.S.G.S. models developed by Frankel et al. (2002). The first model is for random areal sources. These are not identified with any tectonic source, but represent historical distributions of seismicity. The second model is for well-studied ("A") fault systems, treated as being solely characteristic. The third model is for poorly understood ("B") fault systems insofar as they are treated as being characteristic two-thirds of the time. The fourth model is for these same ("B") fault systems insofar as they are treated in terms of the Richter magnitude-occurrence law one-thirds of the time.

For each of these models, earthquakes are randomly selected in accordance with the rates of occurrence as provided in Frankel et al. (2002) and supporting documents (http://geohazrds.cr.usgs.gov/eq/). So, for each year of the random walk ("walkthrough"), random generators determine first whether or not one or more earthquake scenarios occur. If one or more occur, random generators then determine where they occur (fault trace), their magnitude, and their surface rupture zone (treated in Frankel et al. as a single line segment). Coastal California data were used for these random walks, and 20,000 year-samples were developed. These can be subdivided as desired into 400 50-year random walks, or in any other way that is suitable. *Latin squares* modeling, which assures that the number of occurrences for say a specific fault zone fairly samples the fractiles of rates prescribed for this fault zone is here used only as an alternative to the baseline model. As mentioned previously, this Latin squares modeling removes the capacity to examine loss variability over diverse exposure periods.

For this baseline model that begins with coastal California earthquake scenarios, there are 21,367 random areal events, 5204 characteristic only events, 5645 events from mixed faults treated characteristically, and 5931 events from mixed faults treated in terms of the Richter law. This large number of coastal California events composed largely of small-magnitude events yields fewer than 1000 events (about 658) that cause damage to the regional Bay Area hypothetical port system.

2.2.3 Strong Ground Motion Model

For estimating strong ground motions, the model in Abrahamson and Silva (1997) was used. It was only necessary to develop estimates of zero-period strong ground motion accelerations. This is the result of the berth vulnerability models, which were expressed relative to earthquake magnitude and zero-period strong ground motions (on firm soil) after engineers had taken into account geotechnical and structural features of the berths, including prospective liquefaction. The estimates of zero-period strong ground motion values were developed using random generators to account for variability in strong ground motion estimates.

2.2.4 Berth Vulnerability Models

The berth vulnerability models were as suggested above developed from very detailed work in previous projects. Berth vulnerability models used express repair costs and downtimes, respectively, as functions of zero-period strong ground motions. These models are deterministic in the sense that uncertainties are not incorporated. That is, any given ground motion value produces a single loss value rather than a distribution of possible losses. Full-scale incorporation of all uncertainties would have been cost-prohibitive. These berth vulnerability models nonetheless express state-of-the-art site-specific detailed engineering evaluations. Four such models were borrowed, one of which covers a much more seismically resistant berth, and three of which cover less seismically resistant berths. Even less seismically resistant berths, however, have a great deal of inertial resistance to earthquakes and so have high damage thresholds relative to thresholds for many other building and other structures.

2.2.5 System Demands

The systems model depends on the downtime estimates developed. It is assumed that if one berth is down, a ship that might normally occupy this berth can go to any other berth that is available—a major port-disaster advantage that derives itself from berth leasing contracts. Hence, for the baseline models, only two berths need to be available for the regional port system to be functioning. It is also assumed that the cost of an hour's downtime is $60 per twenty-foot-equivalent (teu) container times 36 containers loaded or unloaded per hour. This systems model does not consider the long-term effects of berths not being available, that is, a permanent decrease in berthing demand as customers moved to alternative ports, a major effect at the Kobe port after the 1995 Hyogoken Nanbu earthquake (see Werner et al., 1997).

2.2.6 Types of Risk Results

The overall model can produce a variety of seismic risk estimates for the system including both estimates of mean annualized loss and various fractile loss estimates (e.g., the 500-year loss). A loss distribution can also be produced for the model. In evaluating benefits of a proposed seismic risk reduction (e.g., seismic upgrade or replacement of a berth), a loss distribution can be produced for the status quo and another loss distribution can be produced for the upgraded or replaced berth.

In addition to risk estimates, the overall model as developed here can also produce a conditional loss distribution given a single scenario (defined by fault rupture zone and moment magnitude). This conditional loss distribution can be useful in validation studies for a single earthquake and also in evaluating sources of variability within an absolute loss distribution produced as part of a risk evaluation.

2.2.7 Buttressing the Monte Carlo Modeling with a Variance Reduction Post-processor

Added to this system model is a model for reducing the variance in the estimates of the mean and various fractiles (also called quantiles), such as the 500-year loss. These variance-reduction techniques, developed for MCEER/FHWA, serve to provide greater certainty in the estimates produced relative to the number of simulations (year-samples) developed. In this project, we have further discovered that this variance reduction model can assist in (a) verifying the application of the other models and (b) bringing to light various potential problems in the development of variance reduction techniques. General techniques used in this variance reduction techniques are all post-sampling techniques (dependent on the number of samples evaluated at any given computer run) and include the use of compound Poisson modeling of the resulting loss distribution, bootstrap sampling, Latin squares (or hypercube) sampling, the use of the exponential distribution as a control function (with an emphasis here on its use with respect to residuals rather than weights as in importance sampling), fractile-based sampling to develop the exponential distribution, and various weighting and reweighting techniques. (See Perkins and Taylor, 2003, Taylor et al., 2004)

Variance reduction in the REDARS study for Memphis employed an exponential control function, a function that often approximates losses. In the berthing case, some of the test loss distributions losses were multi-modal rather than exponential, and variance reduction techniques would require an alternative control function, starting simply with a multilinear system for which a minimal defining run of losses would be larger than for an exponential shape.

2.2.8 The Funnel Test for Evaluating Proposed Variance Reduction Techniques

One of the useful tests that we have devised for both verifying computer simulation applications and for examining loss distributions resulting from these applications is the funnel test. Figure 2 illustrates by way of a failed example how this test is used. In each figure, the X-axis represents an increasing number of simulations (up to 20,000 years sampled). The Y-axis represents the total loss estimated ($000s). Provided are the mean loss estimate and its 2.5th and 97.5th centile estimates. The funnel test succeeds when about 95th percent of the time the final mean estimate lies within these 95th centile boundaries for all samples. The funnel test fails when as in Figure 1-2 the final mean clearly does not fall about 95 percent of all samples within the 95th centile boundaries. .

2.3 EXPLORING EXOGENOUS UNCERTAINTIES IN THIS BASELINE MODEL

To explore exogenous uncertainties, alternative models and assumptions are developed to assess the sensitivity of outcomes to these alternative models and assumptions. These include:

- Source model uncertainties such as uncertainties in estimates of prospective earthquake magnitudes and uncertainties in modeling nucleation points.
- Attenuation/amplification model uncertainties such as effects of uncertainties based on source directivity and in modeling soil material properties.
- Structural vulnerability model variations resulting from incorporating uncertainties in source and soil material properties.
- System vulnerability model uncertainties resulting from varying the geographic locations of berths and modifying the shipping demands on the system.
- Economic model uncertainties resulting from consideration of various constant dollar discount rates.

These uncertainties will be explored in greater detail in sections 3.0 and 4.0.

SECTION 3
EFFECTS OF EXOGENOUS UNCERTAINTIES ON SEISMIC PERFORMANCE OF STRUCTURES

3.1 OBJECTIVE

This section provides procedures and results to illustrate how exogenous earthquake source and site uncertainties considered in this project can affect the seismic performance and design requirements of simple inelastic structures that typify many types of structures commonly encountered in lifeline systems nationwide. In this, the simple structures are characterized by inelastic response spectra and yield point spectra, in terms of displacement ductility ratios, drift limits, and associated natural periods and yield strengths and displacements.

The remainder of this section is organized into two main parts. The first part (Section 3.2) references the procedures used to estimate the ground motions as a function of the exogenous source and site uncertainties that were considered, and describes the procedures used to analyze the effects of these uncertainties on the seismic response and design requirements for simple inelastic structures. Then, Section 3.3 describes the results of these structural analyses and the sensitivity of the analysis results to the exogenous uncertainties considered.

3.2 SCOPE

3.2.1 Overview

This analysis consisted of the following steps:

- ***Ground Motions.*** Development of three sets of 30 ground motions per set that represent effects of exogenous uncertainties in earthquake source characteristics and site characteristics. The source characteristics that were varied were hypocenter location (directivity) and asperity location, and the site characteristics that were varied were shear wave velocity, depth to rock, and equivalent-linear shear modulus and hysteretic damping. The three sets of ground motions that were developed considered, respectively, source uncertainties only, site uncertainties only, and both source and site uncertainties. The procedures used to compute these ground motions are summarized in Section 3.2.2.

- ***Response of Simple Inelastic Structures.*** The above ground motions were applied to simple single-degree-of-freedom inelastic structures, in order to: (a) develop inelastic response spectra that show how effects of the exogenous uncertainties on peak structural response depend on the structure's natural period and ductility ratio; and (b) show, for an example four-story building, how the building's design requirements are affected by these exogenous uncertainties. The procedures used for these analyses are summarized in Section 3.2.3.

3.2.2 Procedure for Estimation of Ground Motions including Source and Site Effects

The procedures used to estimate ground motions considering various source and site uncertainties are described in Appendix A, which also contains the various ground motion time histories and response spectra that were developed.

3.2.3 Procedure for Analysis of Response of Simple Structures

Single-degree-of-freedom (SDOF) oscillators can be used to illustrate the response of simple structures and as a basis for estimating the displacement response of a wide range of structure types. The influence of exogenous source and site uncertainties on the peak response of SDOF oscillators having various natural periods and ductility demands can be represented graphically. In this, the single-degree-of-freedom oscillators have viscous damping equal to 5% of critical damping and a bilinear load-deformation relationship that is characterized by the yield displacement, Δ_y, yield strength, V_y, yield strength coefficient, C_y (which is the ratio of V_y to the dead load or reactive weight of the structure W), peak displacement, Δ_u, displacement ductility demand $\mu = \Delta_u / \Delta_y$, and post-yield stiffness (Fig. 3-1). In this project, the post-yield stiffness was set equal to 5% of the initial pre-yield stiffness

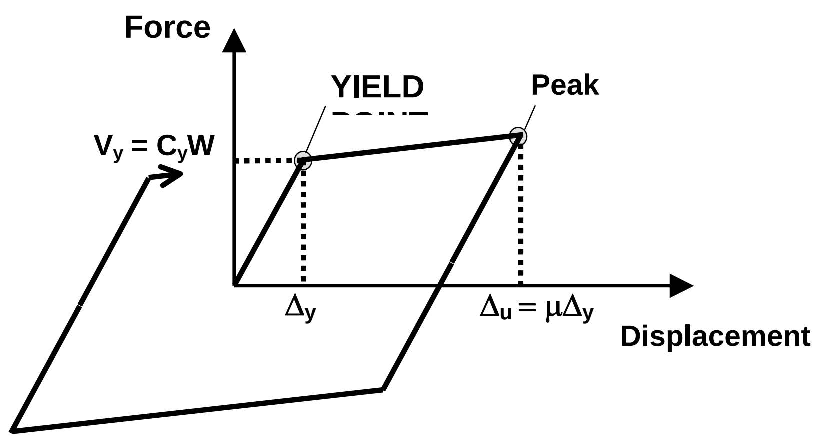
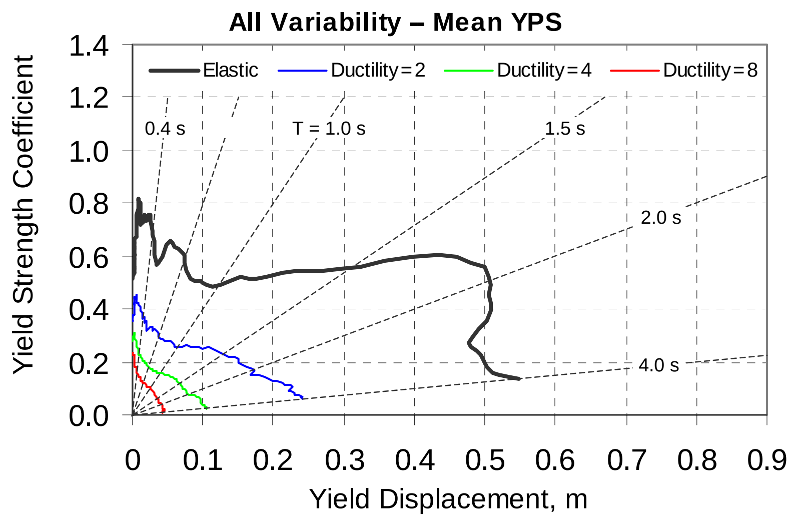


Figure 3-1. Bilinear load-deformation model.

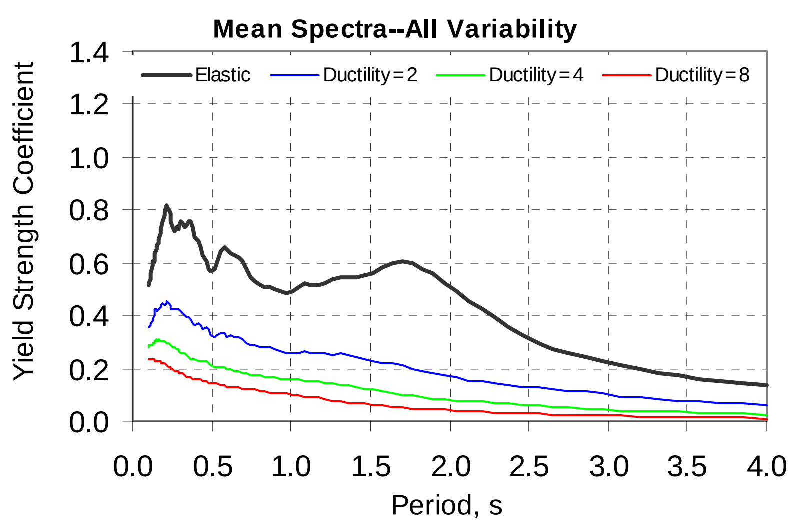
In this project, the peak response of this simple structure is represented as: (a) yield point spectra (YPS), and (b) corresponding inelastic response spectra (IRS). These two types of spectra both show, although in different formats, the yield strength required for the peak displacement ductility demand to equal a specified fixed value, as a function of the natural period of vibration or yield displacement, depending on the spectral format (Aschheim and Black, 2000). Figure 3-2 illustrates equivalent YPS and IRS extracted from results of this project. In the YPS format, the natural period of vibration is constant along a radial line emanating from the origin, and has the values (in seconds) indicated in the figure. The yield displacement is related to the natural period of vibration, T, and yield strength coefficient as follows:

$$\Delta_y = \left(\frac{T}{2\pi}\right)^2 C_y g \tag{3-1}$$

where g = the acceleration of gravity. Equation 3-1 is used to convert the YPS to equivalent IRS.



a) Yield Point Spectra



b) Inelastic Response Spectra

Figure 3-2. Equivalent Inelastic Spectra for Displacement Ductility Ratios of 1, 2, 4, and 8

For each ground motion time history representing the combinations of exogenous source and site parameters listed in Appendix A, constant ductility spectra were generated using the USEE software package, developed at the University of Illinois (Inel et al., 2000). Then, for each grouping of exogenous uncertainties for which ground motion time histories were developed, (i.e., for site uncertainties only, source uncertainties only, and simultaneous source and site uncertainties), results at each period and ductility value were statistically evaluated to obtain means and standard deviations. Spectral representations of mean values, mean ± one standard deviation values, and coefficients of variation (ratio of standard deviation to mean) are presented in Section 3.3. These plots demonstrate the ranges of natural periods and displacement ductility ratios that are most sensitive to the various exogenous uncertainties considered, and illustrate how these exogenous uncertainties affect the strengths required to obtain a desired response in the design of new structures.

3.3 RESULTS

This section shows how the exogenous source and site uncertainties considered in this project affect: (a) ranges of natural periods of simple structures for which these various uncertainties are most important; and (b) design requirements one type of simple structure -- a four-story steel frame building that can typify administration, engineering or computer/equipment-housing buildings within a lifeline system. In this, we consider that the seismic performance of such a structure will depend on both its strength and ductility. Both of these parameters must be specified in order to assure adequate levels of post-earthquake functionality, damage control, and/or life-safety protection during various levels of ground shaking. In general, these strength and ductility requirements, and their associated seismic performance requirements, will depend on the owner's cost, risk, and functionality constraints. For example, a building in an electric power lifeline system that houses equipment and computers that are essential to providing the community with power after an earthquake will usually be designed to more stringent seismic performance requirements and associated strength and ductility levels than will more conventional buildings that do not have such a vital post-earthquake functionality requirement.

In what follows, two sets of results are shown. First, Section 3.3.1 shows IRS comparisons for the various sets of exogenous uncertainties considered in this project, in order to illustrate the ranges of natural periods over which each of these uncertainties is most important. Then, Section 3.3.2 examines the YPS for the various exogenous uncertainties, in order to illustrate the effects of these uncertainties on building design requirements (i.e., building strengths and ductilities required to achieve a desired level of seismic performance.)

3.3.1 <u>Results from Examination of Inelastic Response Spectra</u>

This subsection summarizes trends observed from examination of IRS that show mean strength demands and coefficients of variation (COV) as a function of natural period, for the cases from this project that involve source uncertainties only, site uncertainties only, and both source and site uncertainties simultaneously. All spectra were developed for displacement ductilities of 1 (for an elastic structure), 2, 4, and 8.

3.3.1.1 Means

Mean IRS for the above sets of exogenous uncertainties are shown in Figure 3-3. This figure shows that the mean IRS obtained for these various sets are generally similar.

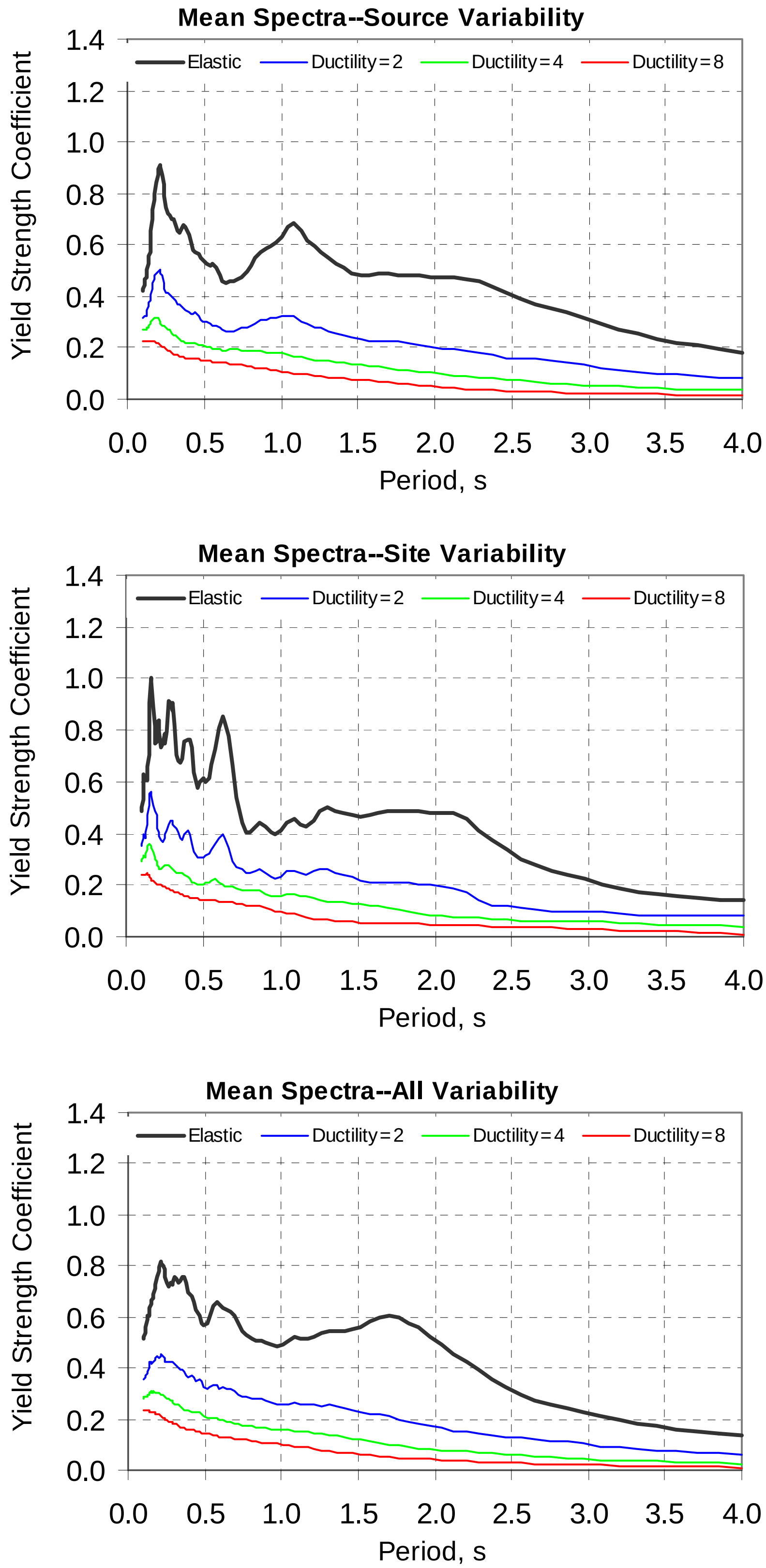


Figure 3-3. Mean IRS for Cases involving Source Only, Site Only, and All Uncertainties

3.3.1.2 Coefficients of Variation

Figure 3-4 presents coefficients of variation of the strengths required to obtain constant ductility responses as a function of period, and therefore illustrates the effects of the various sets of exogenous uncertainties on the seismic performance of simple inelastic structures. The following trends are observed from these figures:

- ***Effects of Exogenous Source Uncertainties.*** The top plot in Figure 3-4 shows that the dispersions in the strengths required to obtain a given ductility response increase with increasing natural period. Thus, these source variability effects are most important for longer-period structures. These trends are generally similar for all ductility ratios considered.

- ***Effects of Exogenous Site Uncertainties.*** The middle plot in Figure 3-4 shows that, for natural periods less than about 0.7 sec., dispersions in the strengths required to obtain a given ductility response depend on ductility level and decrease with increasing natural period. At periods longer than about 0.7 sec., the dispersions associated with site uncertainties are smaller. Thus, the top and middle plots in Figure 3-4 show that, at short periods, the dispersions due to site uncertainties exceed those due to source uncertainties whereas, at longer periods, the opposite is true.

- ***Effects of Simultaneous Source and Site Uncertainties.*** The bottom plot in Figure 3-4 shows that the dispersions in constant-ductility strengths are approximately independent of natural period, but display a dependency on ductility ratio at short periods.

3.3.2 <u>Results from Examination of Yield Point Spectra</u>

3.3.2.1 Effects of Exogenous Uncertainties on Acceptable Design Region

Figures 3-5 to 3-7 show mean strength demands and mean +/- one standard deviation strength demands in the Yield Point Spectra (YPS) format. While the mean spectra are generally similar, dispersion due to source and site uncertainties causes the bands in the spectra at any ductility level to vary in width as a function of period. Thus, the strength needed to limit the structure's peak displacement (or ductility) response of a structure to a desired level depends on the uncertainties considered.

The remainder of this section demonstrates this trend for an example case involving the design of a four-story steel moment-resistant frame building subject to specified performance criteria. This example also serves as an illustration of a procedure that, although some details will differ, can also be used to demonstrate this same trend for a wide variety of non-building structures in lifeline systems (e.g., bridges, wharves, tanks, etc.).

The first step in developing this example is to establish the criteria for acceptable seismic performance of the structure. For this example, the following criteria are assumed: (a) the peak roof displacement is limited to 2.5% of the height of the building, to be consistent with the drift limits suggested in FEMA-273 (1997) for a Life Safety performance level for buildings; and (b) in order to limit structural damage, the system ductility should not exceed 4.

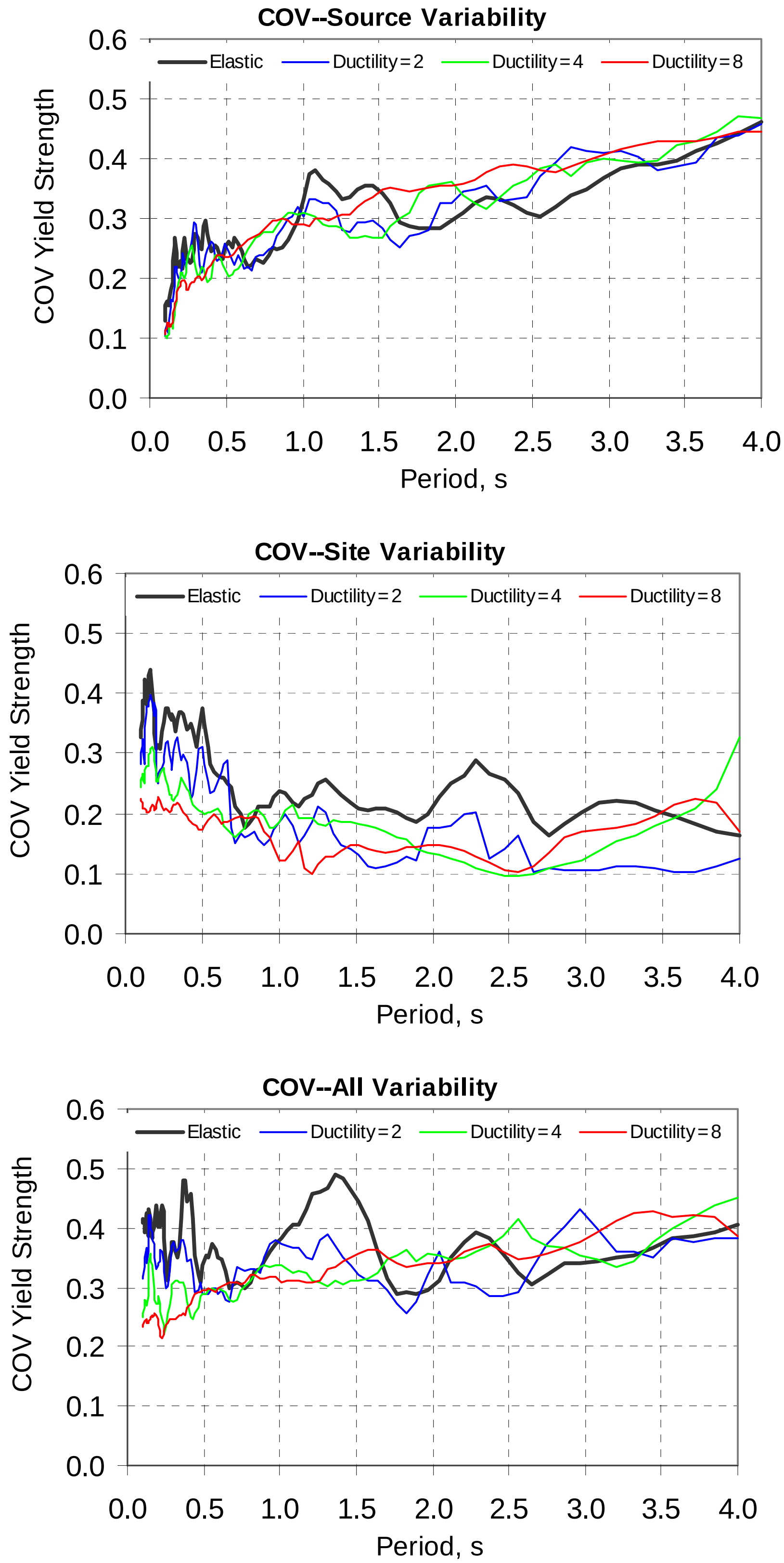
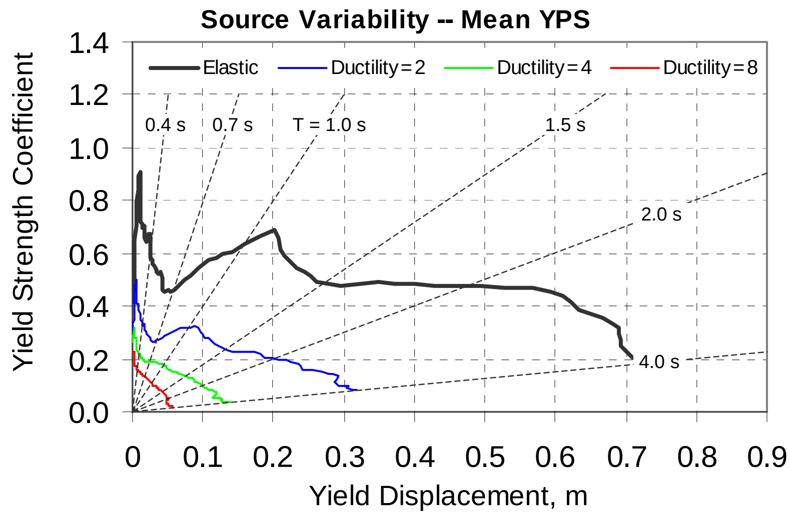


Figure 3-4. COV IRS for Cases involving Source Only, Site Only, and All Uncertainties



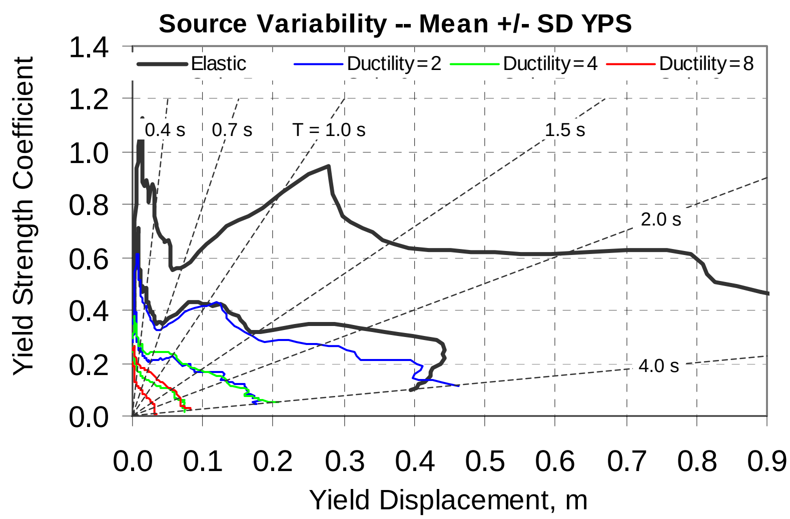
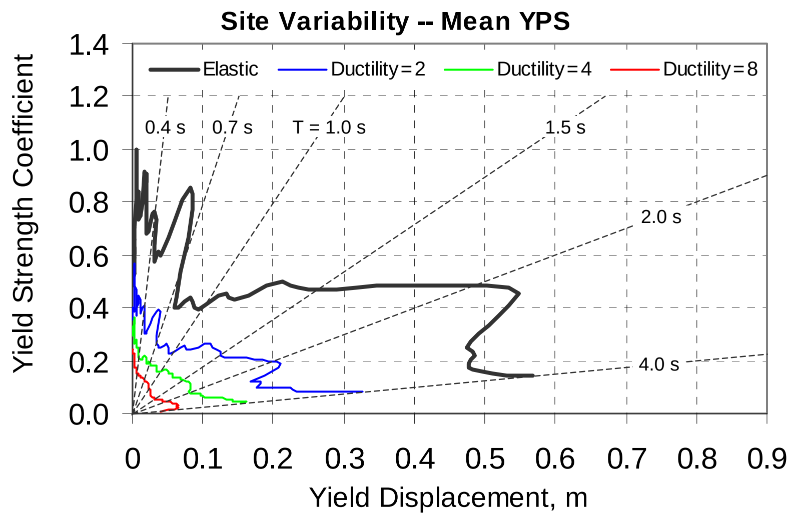


Figure 3-5. Source Uncertainties Only: Yield Point Spectra shown as Plots of Yield Strength Coefficient vs. Yield Displacement for Various Displacement Ductility Ratios



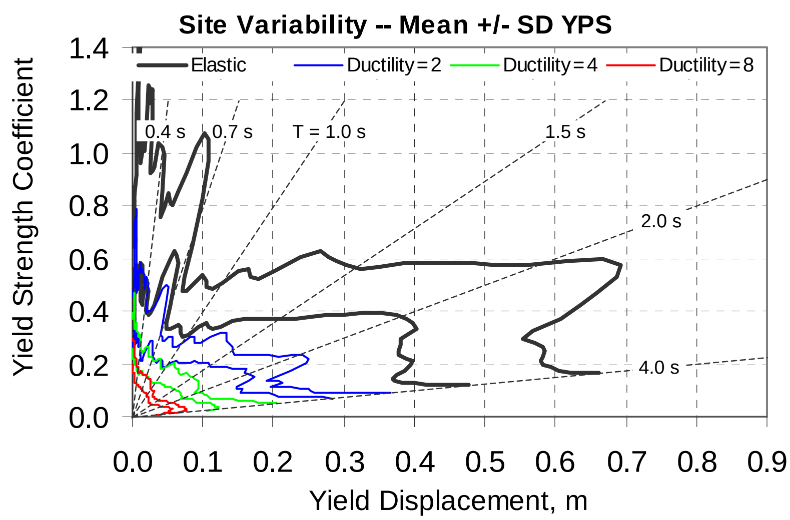
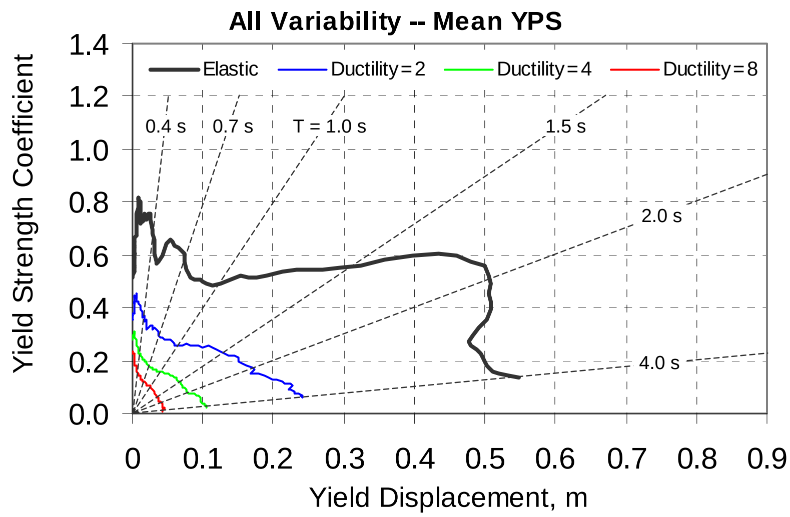


Figure 3-6. Site Uncertainties Only: Yield Point Spectra shown as Plots of Yield Strength Coefficient vs. Yield Displacement for Various Displacement Ductility Ratios



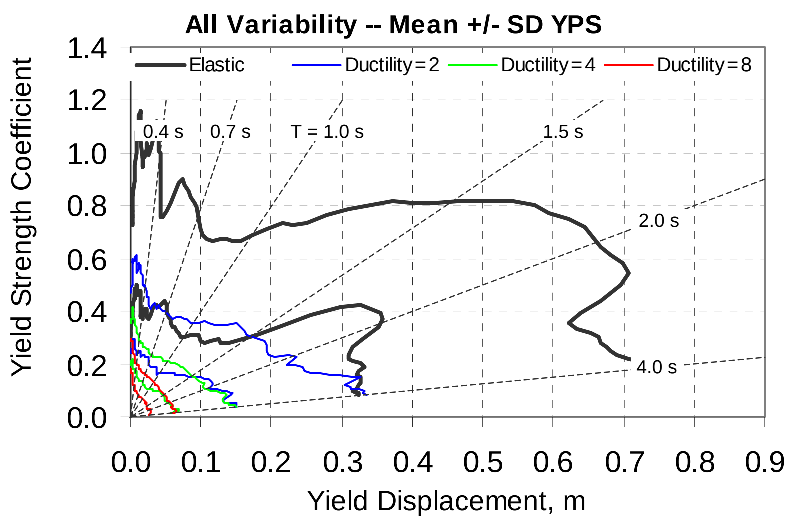


Figure 3-7. Combined Effects of Source and Site Uncertainties: Yield Point Spectra shown as Plots of Yield Strength Coefficient vs. Yield Displacement for Various Displacement Ductility Ratios

Next, assuming that the building has story heights of 13 ft, the peak roof displacement limit is computed as (0.025)(4 stories)(13 ft/story)(12 in/ft) = 15.6 in. Based on data from Aschheim (2004), the frame modal-mass coefficient is estimated to be 0.87 and the frame modal-participation-factor is estimated to be 1.30. Then, following techniques described in ATC-40 (1996), a single-degree-of-freedom (SDOF) system may be defined to characterize the displacement response of the building. For this SDOF system, the peak displacement is computed to be 15.6 in./1.30 = 12 in. = 0.305 m.

Finally, the above calculations are used in conjunction with techniques from Aschheim and Black (2000) to establish an Admissible Design Region (ADR), which consists of those yield points (i.e., combinations of yield strength and yield displacement) that result in acceptable performance as defined above for this building. The process for accomplishing this is as follows:

- To limit system ductility to less than 4, those yield points below the $\mu = 4$ curve must be excluded, as shown by the green shaded region in the upper plot of Figure 3-8.

- Furthermore, to limit the peak displacement to less than 0.305 m, additional yield points must be excluded, which are represented by the tan shaded area in the upper plot of Figure 3-8. This area is established by determining a family of yield points whose product of their yield displacement and their displacement ductility equals the peak displacement of 0.305 m.

  - Points A, B, and C in the upper plot of Figure 3-8 are examples of such points. Point A corresponds to an elastic oscillator with a ductility of 1; thus, its yield displacement equals 0.305/1 = 0.305 m. Point B corresponds to a ductility of 2 and therefore has a yield displacement of 0.305/2 = 0.153 m. Similarly Point C, which has a ductility of 4, has a yield displacement of 0.305/4 = 0.076 m.

  - Thus, a curve passing through these points represents approximately the combinations of strength and stiffness that result in a peak roof drift of 2.5%. This curve extends beyond the elastic spectrum along a radial line of constant period. It defines the portion of an admissible design region governed by drift limits; i.e., weaker oscillators have larger ductility demands and hence exceed the 2.5% drift limit.

- In general, these exclusions as required to satisfy a structure's ductility and drift criteria will result in a "V" or valley-shaped curve to define the lower boundary of the ADR. The valley-shaped curve is termed a "Demand Curve," as indicated in the upper and lower plots of Figure 3-8.

- The upper plot in Figure 3-8 demonstrates the Demand Curve that was developed for this example building, from the mean of the YPS for the exogenous source uncertainties considered in this project. Variability in structural response owing to these source uncertainties is considered in the lower plot of Figure 3-8, as Demand Curves at the mean – one standard deviation and the mean + one standard deviation levels.

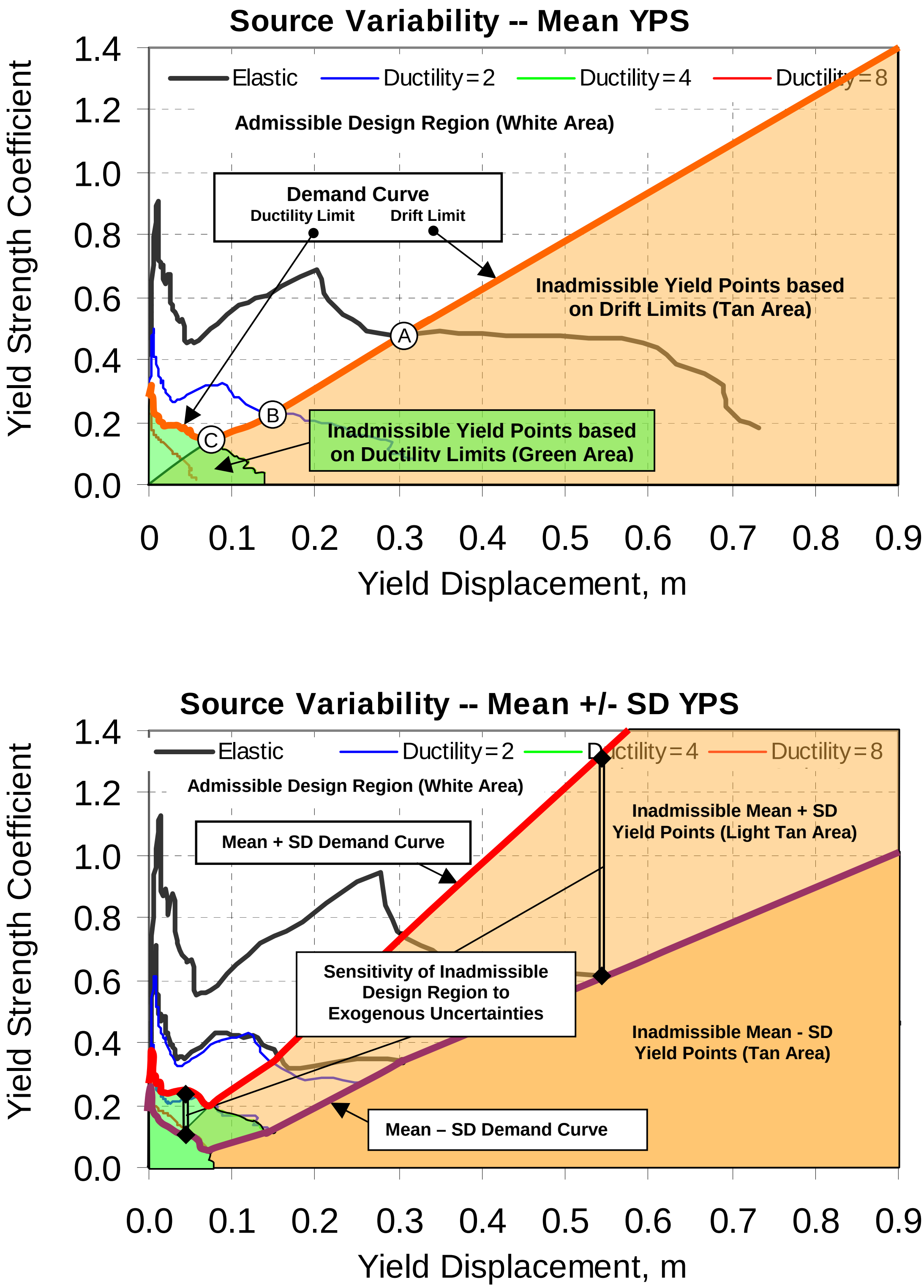


Figure 3-8. Admissible Design Regions Considering Effects of Exogenous Source Uncertainties, for a Four-Story Steel Moment-Resistant Frame Building

ADRs and Demand Curves considering site uncertainties only and combined source and site uncertainties are shown in Figures 3-9 and 3-10 respectively. These figures show that, for this particular example, the Demand Curves are generally most sensitive to the source uncertainties and are least sensitive to the site uncertainties. This sensitivity can, of course, differ for different structures, depending on their structural characteristics and seismic performance criteria.

3.3.2.2 Effects of Exogenous Uncertainties on Base Shear Coefficients

The foregoing YPS can also be used to establish effects of exogenous uncertainties on the design forces for the structure. This is illustrated below, by assessing the effects of the exogenous source and site uncertainties on the base shear strength for the four-story steel frame building considered in the above example.

For this structure, let us assume beam spans are approximately 32 ft. For this case, the building's yield displacement is estimated from a first mode pushover analysis to be 1.25% of the height of the building. It is desired to estimate the sensitivity of the building's mean base shear strength to the combined effects of the exogenous source and site uncertainties considered in this example. When the mean YPS due to these uncertainties are considered (see upper plot in Figure 3-11) the corresponding base shear strength is estimated as follows:

- The roof displacement at yield is estimated as (0.0125)(4 stories)(13 ft/story)(12 in/ft) = 7.8 in. The yield displacement of the corresponding "equivalent" SDOF system is 7.8 in / 1.30 = 6.0 in. = 0.152 m. For this yield displacement, the upper plot in Figure 3-11 shows that a yield strength coefficient of 0.20 or greater would be sufficient to limit the peak roof displacement to 2.5% of the building height and the system ductility to 4 or less.

- Because approximately 87% of the mass is estimated to participate in the first mode, the base-shear coefficient is (0.87)(0.20) = 0.17. This indicates that a base shear strength equal to 17% of the seismic weight of the building is required to obtain the desired performance. If only the mean YPS from these exogenous uncertainties are considered, this base shear strength can be used for the preliminary design of the moment-resistant frame.

- Now suppose that the designer also wishes to examine the effects of the variability of the building's inelastic response due to these source and site uncertainties, before deciding on the level of base shear strength to be used in the preliminary design. To accomplish this, the above steps can be applied to the mean + standard deviation and the mean – standard deviation YPS shown in the lower plot in Figure 3-11.

- This plot shows that the corresponding yield strengths are 0.35 for the mean plus standard deviation YPS and 0.05 for the mean – standard deviation YPS. The resulting base shear strengths are (0.87)(0.35) = 0.30, and (0.87)(0.05) = 0.04 respectively. Thus, for this example, the exogenous uncertainties cause a large variation in the design base shear strength -- which should be considered when selecting the base shear strength for preliminary design.

As previously noted for the ADR, the above trends hold for this particular example only, and may differ for different structures, exogenous uncertainties, and seismic performance criteria.

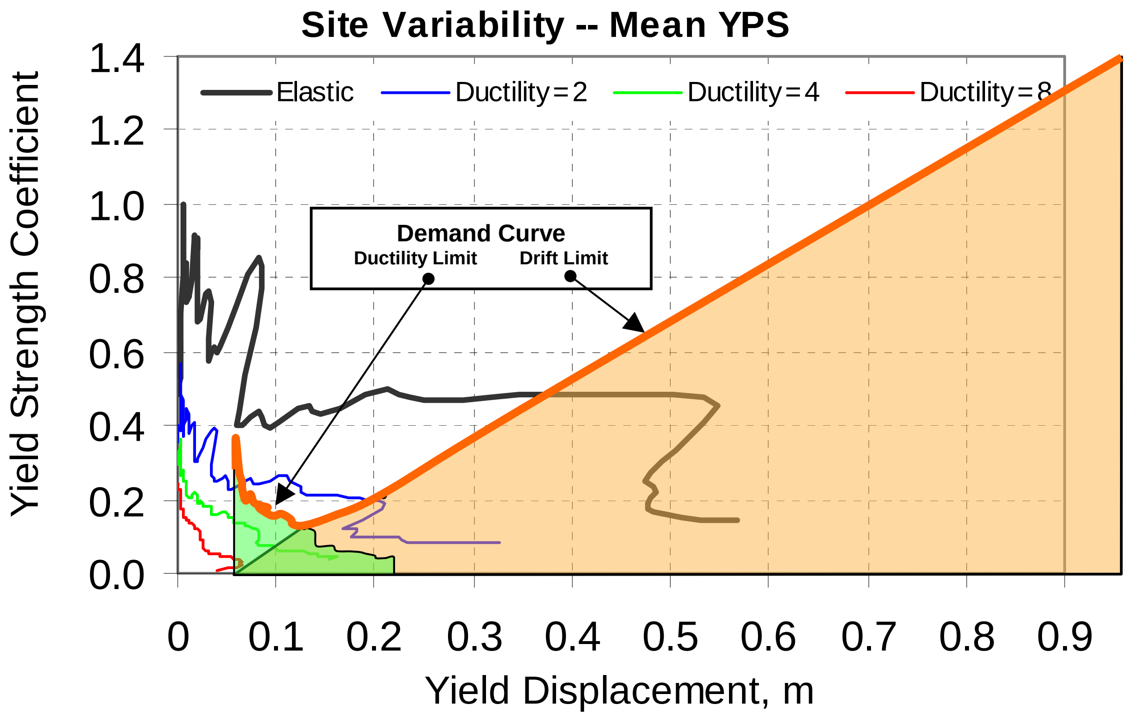


Figure 3-8. Admissible Design Regions Considering Source Uncertainties Only, for a Four-Story Steel Moment-Resistant Frame Building.

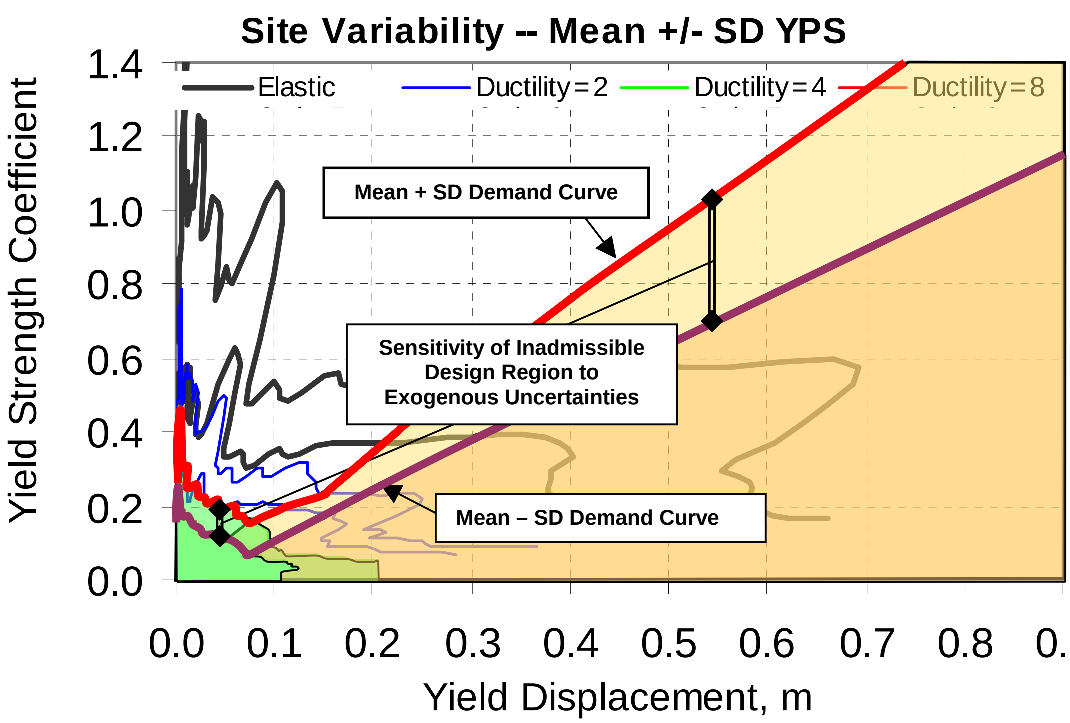


Figure 3-9. Admissible Design Regions Considering Combined Effects of Source and Site Uncertainties, for a Four-Story Steel Moment-Resistant Frame Building

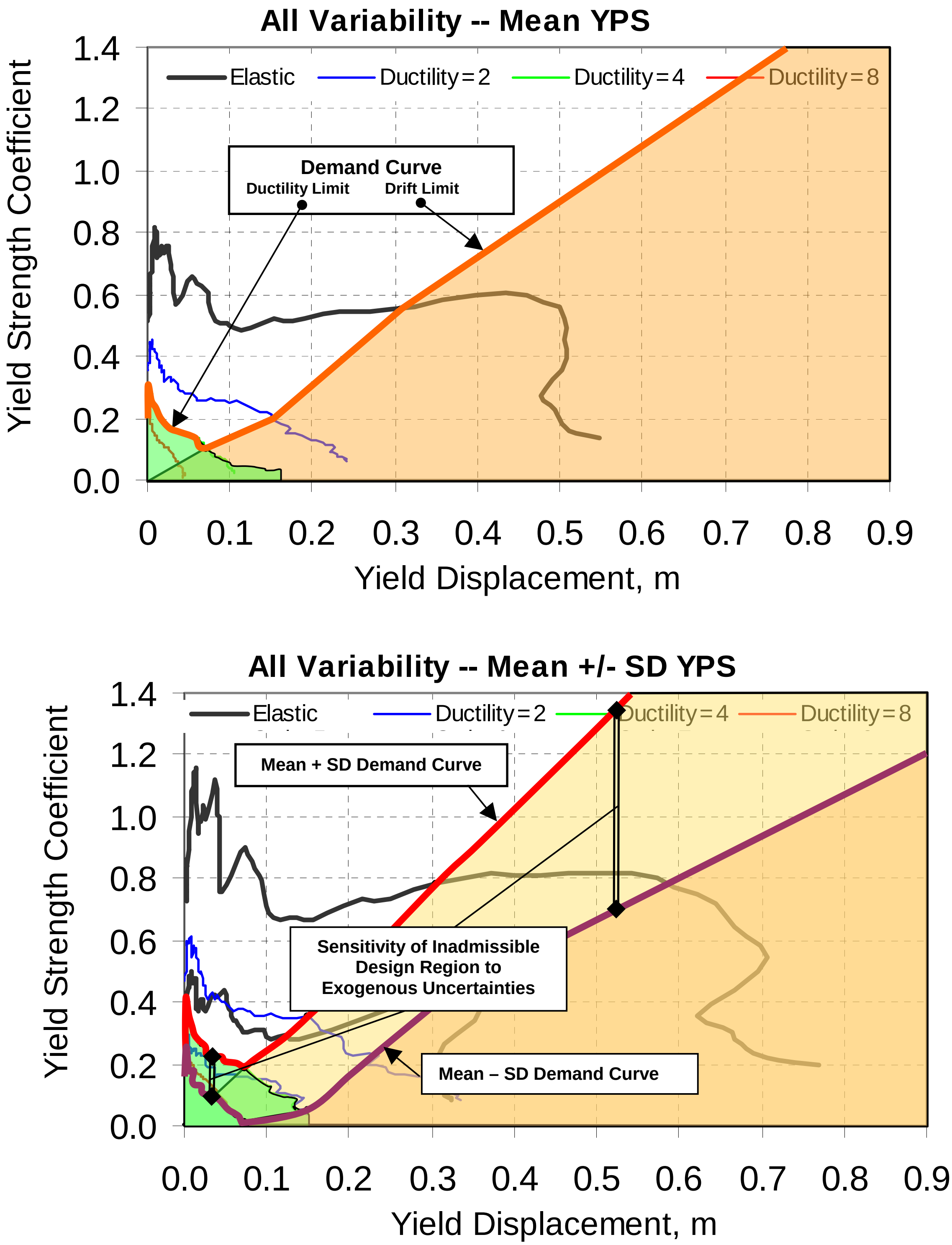
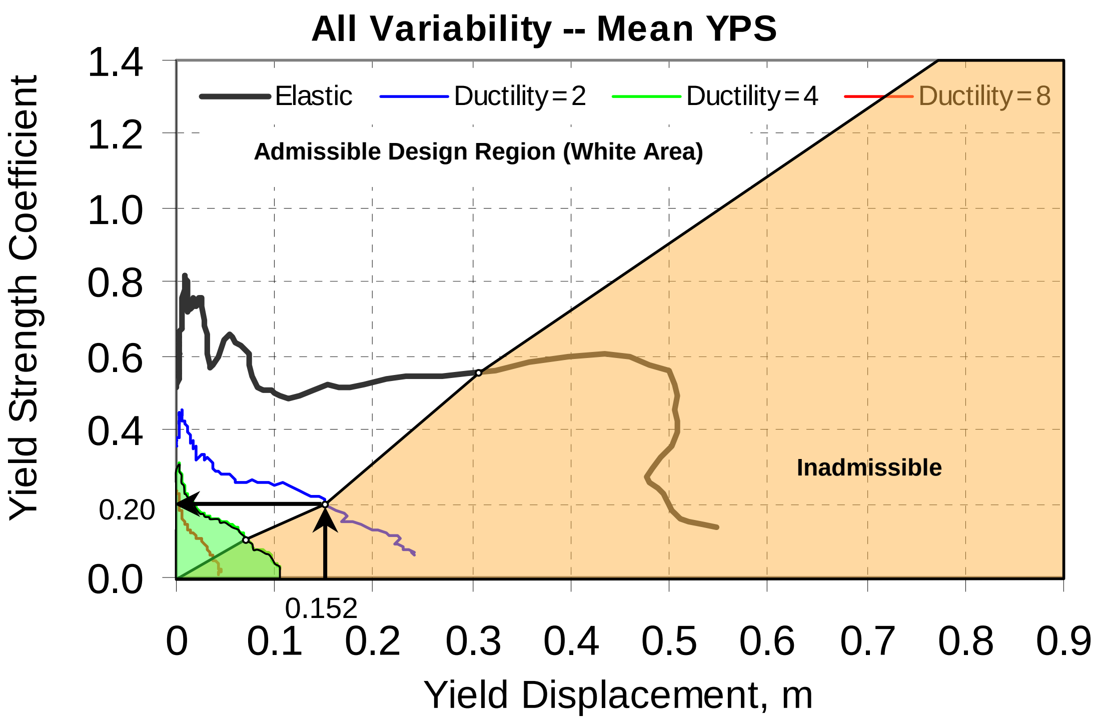


Figure 3-10. Admissible Design Regions Considering Combined Effects of Source and Site Uncertainties, for a Four-Story Steel Moment-Resistant Frame Building



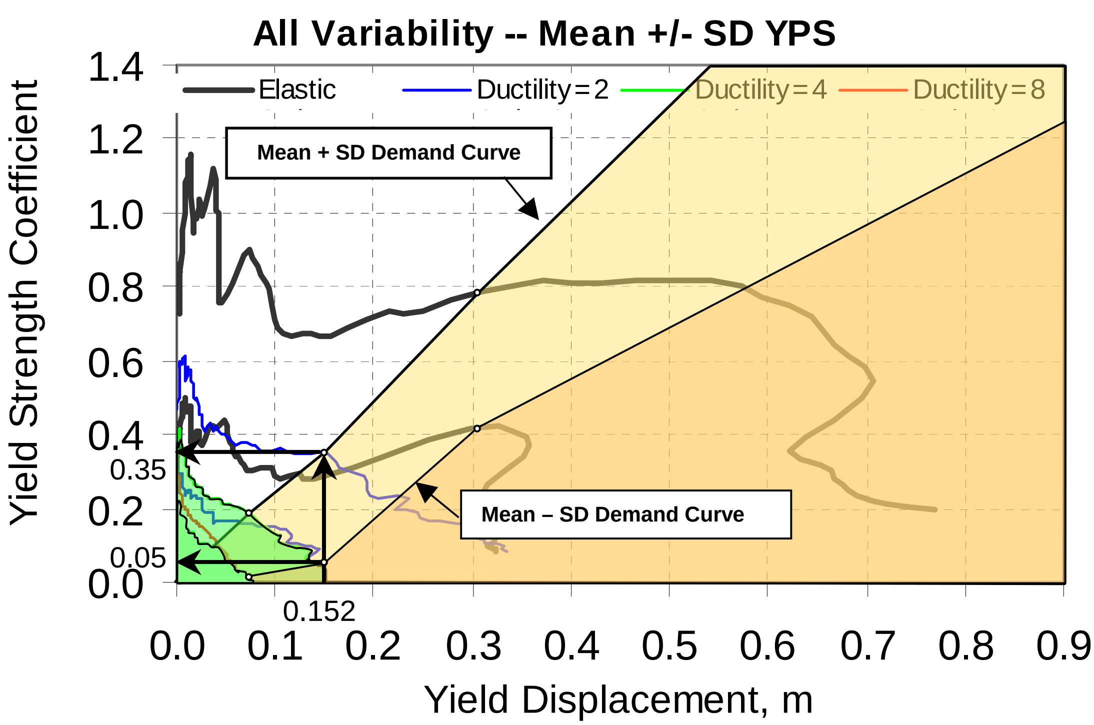


Figure 3-11. Determination of Required Yield Strength Coefficients Based on Estimated Yield Displacements for a Four-Story Steel Frame Moment Resisting Building

SECTION 4.0
SYSTEM RESULTS FROM EXPLORING ENDOGENOUS AND EXOGENOUS UNCERTAINTIES

4.1 OVERVIEW

The following subsections provide illustrative results of evaluating uncertainties for this hypothetical regional berth system. First, in sub-section 4.2, effects of varying geographic locations of the four berths are explored in order to estimate prospective geographic diversification. Second, in sub-section 4.3, results incorporating endogenous uncertainties in the baseline case are provided. Third, in sub-section 4.4, a PHSA is provided as an intermediate output of the modeling—subject to the caveat that alternative pre-sampling methods are available that attain numerical accuracies more rapidly—that is with fewer simulations. Fourth, in sub-section 4.5, the baseline case is explored relative to a seismic decision alternative, in this case an alternative having a berth with a lesser seismic design than its substitute in the baseline case. This use of a seismic decision alternative clarifies how in a practical context the goal is not merely loss estimation but instead the reduction of overall total costs and risks—however this is formulated. Explored briefly in this sub-section are impacts of uncertainties in discount rates used. Fifth, in sub-section 4.6, the issue of uncertainties in estimates of rates of occurrence is indirectly explored through the evaluation of magnitude uncertainties. These are evaluated not only for the baseline case, but for its alternative as well. Sixth, in sub-section 4.7, uncertainties in shipping demands are explored. These appear to have a very significant impact on overall risk and risk reduction estimates.

4.2 IMPACTS OF GEOGRAPHICAL DISTRIBUTION AND SELECTION OF BASELINE LOCATIONS

Typically not studied, the overall impacts of geographical distribution are of general interest in assuring that the regional ports can handle incoming cargo. In this case, baseline assumptions are made except that the berths are varied in terms of their sites. In general, these variations include two berths at Oakland, one berth at Richmond, and one berth at San Francisco. This leads to twelve possible combinations of the four berths. However, three additional possibilities are added: all berths at Oakland, all berths at Richmond, and all berths at San Francisco. These are added to weigh the consequences—given all the modeling assumptions—of putting all berths at one site.

Table 4-1 summarizes these combinations of berths. In general, one would not expect much variation in average annualized total losses (losses from berth damage plus throughput losses). In fact, the analysis of these combinations indicates that the highest average annualized loss is only 11% higher than the least loss. One might though expect the coefficient of variation to vary somewhat more owing to the three geographically non-diversified cases below (cases 13 through 15). However, the highest coefficient of variation is less than 6% higher than the lowest coefficient of variation. The range of variances is somewhat greater, with the highest variance being 29% higher than the lowest variance. The average probability of some earthquake damage (here called “lambda”) varies from 2.0% (for the bottom single site alternatives) to 3.3%, but lambda in this context has almost an inverse correlation with other key factors. Of importance in showing impacts of diversification, it turns out, are estimates of downtimes. The final column in Table 4-1 shows how average downtime estimates for a 50-year period range from 100 days to 156 days—the latter applying to one of the single-site alternatives.

In general, geographic diversification has some slight effect in the regional port system. However, the possible berth sites considered in the San Francisco Bay region are generally too close to each other for extremely dramatic result. Any results in this study must be moreover be regarded as being based on a number of assumptions that do not realistically portray many of the soil, transportation, and other factors of significant importance in looking at regional diversification factors.

Based on least downtime, the third case below was selected as the baseline case. Of significance, this case includes the two least seismically vulnerable berths at Oakland and the most vulnerable berths at Richmond and San Francisco, respectively.

Table 4-1
Hypothetical cases involving alternative locations
Of berths at San Francisco, Richmond, and Oakland, and
Resulting average downtime estimates

Case	Highly vulnerable berth	Less vulnerable berth	Highly vulnerable berth	Less vulnerable berth	Average 50-year downtime (days)
1	SF	Richmond	Oakland	Oakland	119
2	Richmond	SF	Oakland	Oakland	124
3	SF	Oakland	Richmond	Oakland	110
4	Oakland	SF	Richmond	Oakland	116
5	SF	Oakland	Oakland	Richmond	119
6	Oakland	SF	Oakland	Richmond	120
7	Richmond	Oakland	SF	Oakland	112
8	Oakland	Richmond	SF	Oakland	117
9	Richmond	Oakland	Oakland	SF	126
10	Oakland	Richmond	Oakland	SF	124
11	Oakland	Oakland	Richmond	SF	121
12	Oakland	Oakland	SF	SF	123
13	Oakland	Oakland	Oakland	Oakland	129
14	Richmond	Richmond	Richmond	Richmond	154
15	SF	SF	SF	SF	156

4.3 ENDOGENOUS UNCERTAINTIES FOR THE BASELINE CASE

Table 4-2 summarizes that basic statistics for the baseline case. These statistics arise from using variance reduction techniques for mean loss estimates and raw bootstrap techniques for various fractile loss estimates. The determination of lambda at the end of Table 4-2 is a determination of the probability of some loss in any given year. Lambda has been a critical parameter in the development of variance reduction techniques for lifeline systems throughout the United States. Lambda is the Poisson parameter in the compound Poisson modeling of earthquake loss distributions (See Perkins and Taylor, 2003).

Note in addition that the standard deviation of the estimate of the average annualized loss could in theory be reduced further through more than 20,000 year-samples. One can in principle produce statistics with 95th centile limits that converge on +/- 0. Were there no exogenous uncertainties, one could believe that one had perfect confidence in the results produced.

Table 4-2 also provides statistics for the contributions of San Andreas faulting events and Hayward faulting events, respectively. As one can see from this table, these two faults provide by far the bulk of the overall losses. This is in spite of the application of random areal sources and the contributions of other specific fault systems, namely, Calaveras North, Concord-Green Valley, Great Valley (faults 4 through 7), Greenville, Huntington Creek-Berryessa, Maacama South, Monte Vista-Shannon, Point-Reyes, Rodgers Creek, San Gregorio, and West Napa.

San Andreas scenarios cause larger losses both with respect to the average annualized loss and also with respect to various fractile estimates. Noticeable is that variance reduction techniques do not apply as well to these specific fault systems as they do to the overall seismicity in the region. The variance reduction techniques are about a multiplicative factor (number of year-samples needed to achieve the same results as are achieved through the use of bernoulli processes) of 1.05 for the San Andreas fault system, 1.67 for the Hayward fault systems, and 3.17 for the overall seismicity in the region. A chief reason why these multipliers are higher for overall seismicity lies in the larger sample (simulation) size used for estimating losses from overall seismicity than the sample size used for estimating losses from individual fault systems.

Table 4-2
Basic Loss Statistics for the Baseline Case

	All earthquake scenarios ($000s)	San Andreas scenarios ($000s)	Hayward scenarios ($000s)
Total Average annualized loss	1027	572	303
Standard deviation of the average annualized loss	9939	8608	4379
Standard deviation of the estimate of the average annualized loss (variance reduction techniques applied)	5577	8415	3387
95th centile limits of the average annualized loss (variance reduction techniques applied)	+/-77	+/-117	+/-47

50-year loss	2,240	0	0
100-year loss	37,836	0	0
500-year loss	133,047	132,504	63,869
1000-year loss	137,851	137,846	80,158
2500-year loss	139,289	138,174	86,086
Lambda (probability of some loss in a given year)	0.0329	0.0047	0.0080

The baseline case to a large extent determines why the San Andreas fault system yields so many losses. In particular, in the baseline case, the two most seismically vulnerable berths are located at San Francisco and Richmond, respectively. Had the most seismically vulnerable berths been selected at Oakland, then the Hayward faulting event(s) would have been the more dominant. The geographical distribution of the four hypothetical berths is itself hypothetical. Results for the baseline case cannot therefore be assumed to apply to the actual berths in the San Francisco Bay region.

Figure 4-1 provides a cumulative loss distribution for the baseline case. The lack of continuity in this case is represented by the gaps at various points within this figure. These gaps could be removed through further simulations with increased certainty. Figure 4-2 provides an account of the 95th centile limits on various fractile estimates (50-year, 100-year, 200-year, 500-year, 1000-year, 1500-year, 2000-year, and 2500-year total losses). Figure 4-5 provides a funnel test for the baseline case. Figure 4-5 demonstrates that variance reduction procedures work extremely well for overall seismicity: the mean from the largest number of simulations falls within the confidence limits for all simulations produced.

Figure 4-1. Cumulative Loss Distribution for the Baseline Case

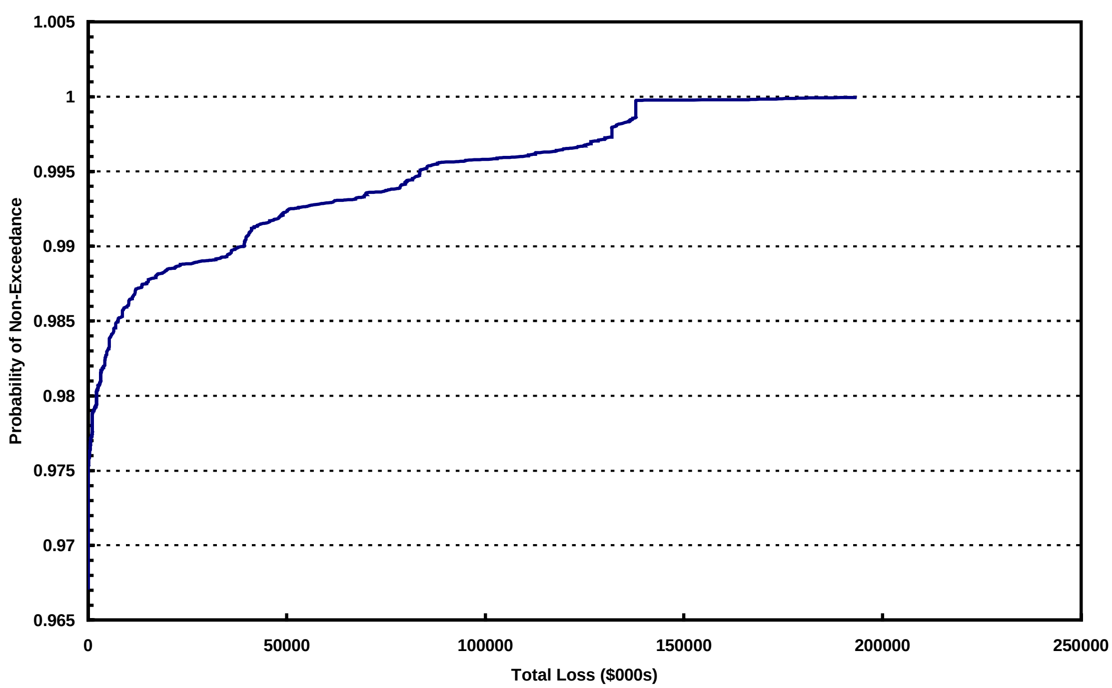


Figure 4-2. Mean Fractile Estimates and 95th Centile Confidence Levels for the Baseline Model

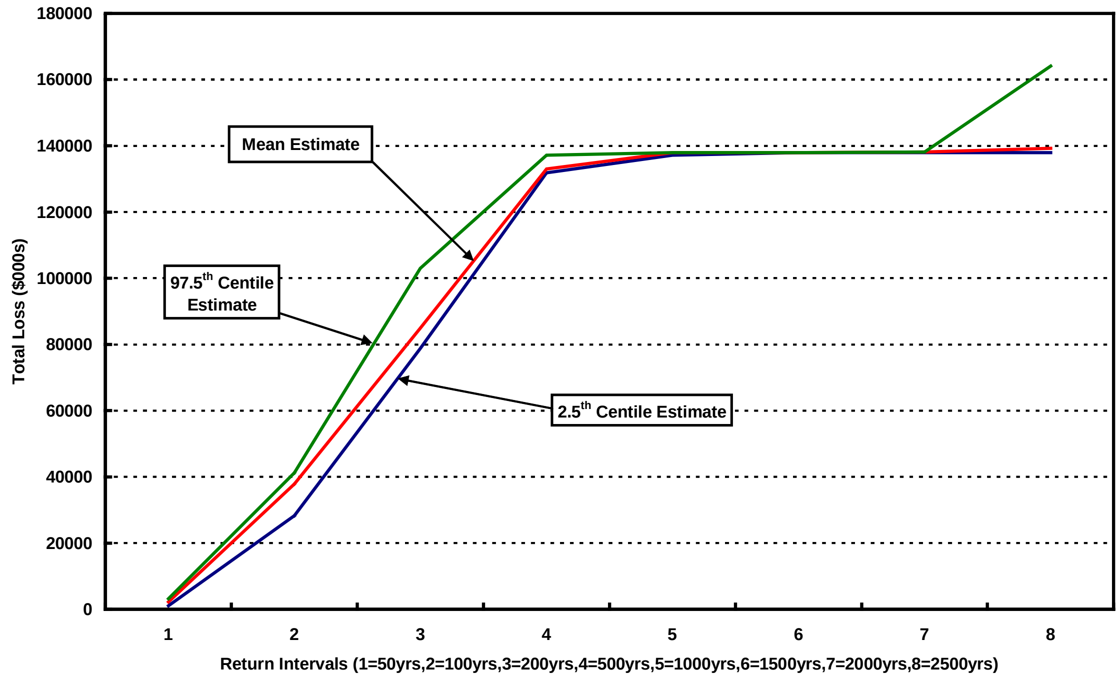
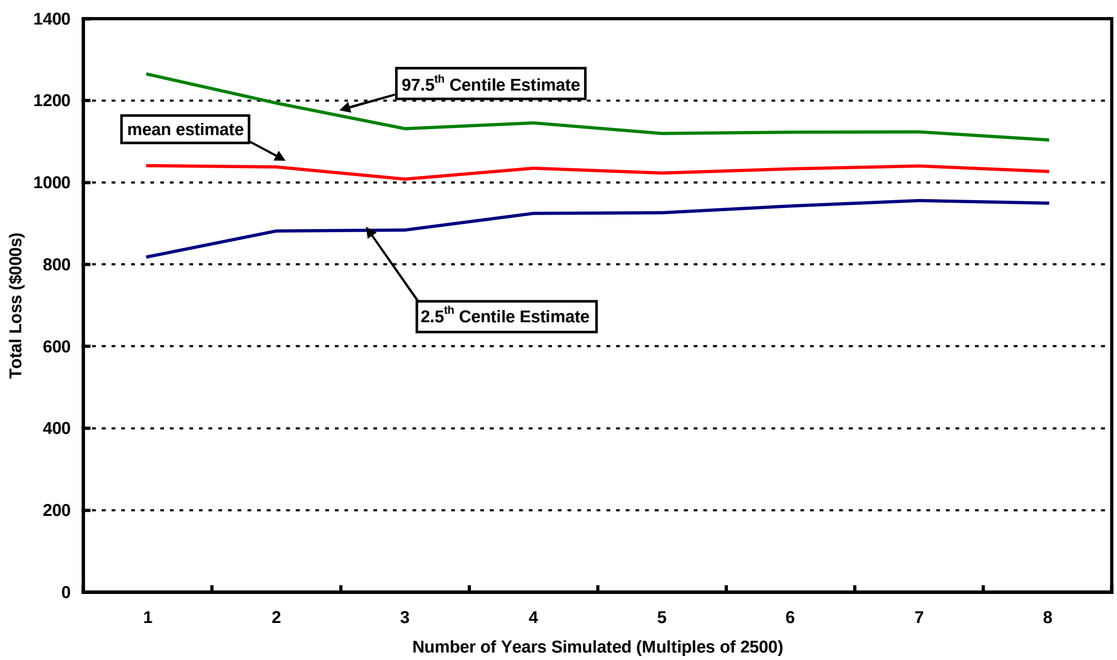


Figure 4-3. Funnel Test for Estimating Mean Total Loss for Baseline Case (Mean Loss Estimated Along With 95th Centile Confidence Limits)



4.4 ILLUSTRATION OF CONFIDENCE LEVELS FOR STRONG GROUND MOTION HAZARD LEVELS

As suggested earlier, the walkthrough method as a basic Monte Carlo method can yield confidence levels and limits for strong ground motion fractile estimates. In this illustration, soil estimates are developed for a particular site. These are not to be understood as B/C boundary estimates as used in seismic building codes and seismic design levels, and the illustration is intended to stress confidence limits rather than specific values. The fractile estimates, moreover, are not derived from any special variance reduction techniques. Instead, again for illustrative purposes, use of the binomial distribution (see Taylor et al., 2000) is compared with the use of bootstrap estimates to show that they parallel each other very closely.

Table 4-3 summarizes these findings with respect to five return interval estimates. Uncertainties in strong ground motions are modeled in these estimates. For reference purposes, without these uncertainties, the 300-year and 500-year estimates both would be 0.56g or 0.57g. The uncertainties clearly increase estimates at these levels. The 95th centile confidence limits for these estimates indicates that more precise estimates could be achieved through either "exhausitive sampling" (numerical integration) as performed at U.S.G.S. or the use or further simulations. As with fractile loss estimates, generally more simulations are needed to develop limits for longer return intervals equivalent to limits for shorter return intervals. However, the major point is that the walkthrough method is consistent with such hazard estimates. Other sampling methods may be more comprehensive, but do not have some of the advantages for systems risk evaluations that the walkthrough method has. In particular, the walkthrough method preserves temporal randomness, so that a number of random walks can be evaluated through an exposure period.

Table 4-3
Illustrative Strong Ground Motion Firm Soil Fractile Estimates (percent g) for a Site

Return Interval	Derived by Binomial Theorem			Derived by 1000 Bootstrap Trials		
	2.5th Centile Estimate	Best Estimate	97.5th Centile Estimate	2.5th Centile Estimate	Mean Estimate	97.5th Centile Estimate
100 years	20%	22%	25%	21%	22%	24%
300 years	43%	47%	52%	44%	48%	52%
500 years	52%	57%	62%	52%	56%	61%
1000 years	61%	71%	80%	61%	71%	80%
2500 years	78%	88%	92%	78%	88%	92%

4.5 COMPARISON WITH A HYPOTHETICAL DECISION ALTERNATIVE

In an actual decision context, there may be one or more options considered at a cost. For sake of putting this hypothetical system into a more realistic context, it has been assumed that one of the more vulnerable berths is a substitute for one of the less vulnerable berths. This presents a decision alternative that could be a wharf seismic upgrade or a proposed higher seismic design level.

Table 4-4 summarizes the differences between this case in which one of the berths has less seismic resistance than in the baseline case. Note that the difference in average annualized losses is $146,000 and there is a significant difference in the standard deviation of this loss. In a non-federal decision, this high standard deviation can play a major role. The case with less seismic resistance also has higher loss values at the 50-year and100-year return intervals. Yet, at the 500-year return intervals and above, the decision alternative with the lesser seismic design has higher losses. One of the key reasons for this result is that the berth with the lesser seismic design has lower repair costs and these lower repair costs are significant whenever very high strong ground motions affect the berth. Likewise, with higher strong ground motion values, repair times approach maximum times.

Evaluating the present value of the average annualized loss differences is a first step in many financial decision procedures. This will vary according to the real discount rate used. At a 3.5% real discount rate, roughly the very long-term difference between government bonds and inflation, for a fifty-year exposure the multiplier for average annualized losses is 23.45. In contrast, a 7% real discount rate was often used in the 1980s and 1990s, and this yields a multiplier of 13.80 and a 2% real discount rate is currently thought to be appropriate (October, 2003; written comm. A. Rose) and this yields a multiplier of 31.42. Hence, the difference in average annualized loss has a present value of $3.45M, or $2.02M, or $4.62M, depending on real discount rate selected. (See Ferrito et al., 1999, for one previous pertinent discussion of this exogenous uncertainty; other helpful discussions are OMB, 1972, OMB, 1992, Moore, 1995, and Lew, 1999)

Table 4-4
Basic loss statistics for the baseline case as opposed
To a lesser seismic design at one of the berths

	Baseline Case ($000s)	Case with Lesser Seismic Design ($000s)	Difference between the two Cases ($000s)
Total Average annualized loss	1027	1174	146
Standard deviation of the average annualized loss	9939	10658	719
Standard deviation of the estimate of the average annualized loss (variance reduction	5577	6376	799

techniques applied)			
95th centile limits of the average annualized loss (variance reduction techniques applied)	+/-77	+/-88	+/-14
50-year loss	2,240	2,886	646
100-year loss	37,836	54,294	16,463
500-year loss	133,047	118,252	(14,795)
1000-year loss	137,851	118,403	(19,448)
2500-year loss	139,289	130,331	(8,958)
Lambda (probability of some loss in a given year)	0.0329	0.0329	0

For benefit-cost evaluations that depend solely on averages and that do not incorporate considerations of the greater certainty in use of higher seismic resistance, selection of the real discount rate will have more than a factor of two bearing on the actual decision. Any seismic upgrade or seismic design that costs more than the present value of average benefits will not have an adequate benefit-cost ratio. Yet, other financial decision procedures will consider as well either the variance on losses or else the entire distribution on losses. (See Alesch et al., 2002)

4.6 EFFECTS OF EXOGENOUS UNCERTAINTIES IN ESTIMATING PROSPECTIVE MAGNITUDE UNCERTAINTIES

Estimates of rates of occurrence are for known active faults also associated with estimates of average fault displacements per event which are also associated with estimates of magnitudes. Here, effects of magnitude uncertainties—associated as well with uncertainties in rates of occurrence, are evaluated.

To evaluate the effects of these magnitude uncertainties, the sensitivity evaluation here considers the effects both on the baseline case and the alternative case considered in section 4.4 of modifying all input magnitudes by 96%, 97%, 98%, 99%, 101%, 102%, 103%, and 104%, respectively. Results of these findings are normalized to the loss statistics found in Table 4-5 so that one can readily view the comparative impacts of these global percent magnitude changes. Table 4-5 summarizes these normalized findings. Because San Andreas and Hayward faulting events dominate the loss statistics in the hypothetical system being evaluated, most of the rate uncertainties in magnitudes will be associated with effects on overall losses from these two faulting systems.

Table 4-5
Comparative Effects of Global Percent Magnitude Changes
On the Baseline Case and Its Alternative

	Global Percent Magnitude Changes Relative to Baseline								
	96%	97%	98%	99%	100%	101%	102%	103%	104%

Total Baseline Losses	0.84	0.88	0.92	0.96	1.0	1.01	1.09	1.13	1.19
Total Alter-native Losses	0.89	0.92	0.95	0.97	1.0	1.04	1.06	1.11	1.16
Total Differ-ences	1.25	1.17	1.12	1.05	1.0	1.03	0.93	0.95	0.96
Differ-ences in Repair Costs	1.21	1.13	1.09	1.03	1.0	0.95	0.90	0.87	0.84
500-year loss	0.82	0.87	0.92	0.96	1.0	1.03	1.04	1.03	1.03
Standard Dev-iation	0.87	0.91	0.94	0.97	1.0	1.02	1.04	1.06	1.09
95th Centile Limits	0.91	0.94	0.96	0.97	1.0	1.03	1.04	1.08	1.10
Lambda	0.85	0.89	0.93	0.97	1.0	1.04	1.09	1.12	1.16

In Table 4-5, as expected, total losses increase as earthquake magnitudes increase. The total losses for the baseline case increase slightly faster than those for the alternative to the baseline case. This becomes apparent in the decreasing rate of change for the total differences between the baseline case and its alternative. As implied in Table 4-4, the major differences between these two cases is greatest at lower return intervals with corresponding lower magnitudes. These major differences diminish as worst-case earthquakes are postulated. A significant part of the explanation of this diminution lies in the reduction in differences in repair costs. At higher strong ground motions caused by earthquakes having higher magnitudes, the higher replacement costs of the berth with a superior design begins to play a significant role in overall repair costs and hence overall costs.

The 500-year loss estimate as indicated in Table 4-5 has a rate of change relative to magnitude changes that increases significantly until the baseline magnitudes used are reached, and then rises very slowly. At some magnitude level, effects of critical berth downtimes do not change dramatically.

The standard deviation for total baseline losses increases somewhat more slowly than do total baseline losses. As an additional note, it can be expected that the baseline or superior seismic alternative will have a lower standard deviation than the inferior seismic alternative except under such conditions as the following: (a) the system in question has evolved so that removing one system element improves system performance or (b) higher repair costs for the superior seismic system outweigh reductions in downtime for the system in question. Neither of these conditions obtains for the hypothetical system in question. The superior seismic design is in this case as in most others the more risk-averse (as regards its standard deviation) system.

As expected, the 95th centile limits as determined through variance reduction techniques have a rate of change that parallels the rates of change of the standard deviation. This is not a foregone conclusion inasmuch as the “lambda,” or probability of some loss, also impacts these 95th centile limits as determined through variance reduction techniques.

Some of the results in Table 4-5 are not to be extrapolated necessarily to other systems. In particular, owing to non-linear effects, one cannot predict in advance for instance total differences between two seismic decision alternatives in a system context.

4.7 EFFECTS OF VARIOUS TYPICALLY EXOGENOUS UNCERTAINTIES IN ESTIMATES OF SHIPPING DEMANDS

Shipping demands are rarely considered in seismic risk evaluations, and even then their uncertainties are almost never considered. Typically shipping demands are based on a current very detailed schedule. This schedule may be developed for several years. Economic forecasts, a major source of uncertainty, may in addition imply that shipping demands will increase at a specific rate over time. Current shipping demands may be well below those in ten, twenty, or fifty years. As a consequence, a more detailed evaluation is possible of the current shipping demands on port berths, but these current shipping demands may not reflect the needed usage of these berths over time.

For this reason, a sensitivity evaluation is here made of the impact of various estimates of shipping demands on the risk results. The baseline assumption is that 2 berths are needed at any given time. This assumption is changed to vary from 0.5 berths to a maximum capacity of 4 berths. Table 4-6 summarizes normalized findings of these assumptions.

In Table 4-6, total baseline losses begin to increase rapidly after 2.0 berth demands. The standard deviations tend to track this non-linear pattern, although at a slightly reduced pace. Differences between loss estimates for the baseline case and its alternative tend to have a plateau at about 3 berth demands.

These effects tend to be the greatest of the various parameters so far examined in this section. Their significance is shown in how the difference in total losses increases very rapidly until it appears to reach a plateau.

Table 4-6
Normalized Results of the Effects of Various
Assumed Shipping Demands on the Hypothetical
Berth System

	Various Demands (Berths Required) Assumed							
	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0

Total Base-line Losses	0.89	0.90	0.95	1.0	1.10	1.19	1.41	1.62
Its Stand-ard Dev-iation	0.87	0.88	0.93	1.0	1.10	1.20	1.34	1.48
Alter-native Total Losses	0.84	0.85	0.93	1.0	1.14	1.29	1.48	1.66
Its Stand-ard Dev-iation	0.83	0.84	0.92	1.0	1.11	1.23	1.37	1.51
Differ-ence in Total Losses	0.50	0.53	0.78	1.0	1.48	1.95	1.95	1.95

SECTION 5.0
CONCLUDING REMARKS

This research has begun to examine how exogenous uncertainties, those not typically modeled, may in some instances be critical to informed decision-making for lifeline systems. Increasingly, rational and efficient procedures are available for synthesizing information for such informed decision-making in which not only seismic hazards, but also structural vulnerabilities and system response are evaluated.

This research on structures (section 3.0) has focused on the use of equivalent Single-Degree-of-Freedom systems to estimate the effects of exogenous source and site uncertainties on the strength required to limit system ductility and peak displacement to designated levels. The evaluation of effects of typically exogenous uncertainties on a four-story steel moment frame building has shown that these uncertainties can have substantial effects on seismic performance and design requirements. These effects depend on the attributes of the structure, the seismic performance criteria considered in the design of the structure, and the exogenous uncertainties under consideration.

Research on system and decision effects of exogenous uncertainties has shown in one instance that discount rates and shipping demands, the latter being commonly ignored, have significant impacts on loss and loss reduction results. Other parameters such as uncertainties in magnitude estimates have in this case been shown to have less impact on loss reduction results.

Numerous additional uncertainties have not been explored. One of the complexities in exploring uncertainties in rates of earthquake occurrence, as derived from paleoseismic studies on slip rates, is that relationships among fault rupture area, average fault slip, moment magnitude, seismic moment, fault rupture length, and fault rupture width need to be expressed together stochastically. Correlation effects generally have not been explored in this research (see VanMarcke and Cornell, 1969). Routinely explored by practitioners, strong ground models and their uncertainties have not here been explored for their effects on seismic risk estimates (see, for instance, Atkinson and Boore, 1997, and Campbell and Bozorgnia, 2002). Only initially explored have been impacts of uncertainties in estimates of liquefaction-induced permanent ground displacements, as well as variable estimates of the response of structures to these displacements. In general, research will typically uncover a variety of overlooked uncertainties if only because models used are never in a stage of full completion.

For structures, other important response quantities are substantially affected by higher modes, which are not represented by the approaches developed in section 3.0. Techniques to extend this research to address higher mode effects on these quantities are available, and should be used to investigate the effects of exogenous uncertainties.

For risk-informed decisions, this research proposes a two-pronged approach. In accordance with research by Porter and others (2002), endogenous uncertainties need to be explored so that efforts can focus on those having the greatest impact on outcomes. At the same time, seismic decision procedures should consider uncertainties typically regarded as exogenous, if only because these could be decisive for informed risk decision-making.

ACKNOWLEDGEMENTS

The investigators thank the United States Geological Survey for this grant and Dr. John D. Unger, External Research, Earthquake Hazards Program, for his assistance. David Perkins has also provided valuable criticisms of an earlier version of this report. The investigators, however, remain solely responsible for the contents of this report.

REFERENCES

Abrahamson, N. A. and W. J. Silva, 1997, "Equations for Estimating Horizontal Response Spectra and Peak Acceleration from Western North American Earthquakes: A Summary of Recent Work," *Seismological Research Letters,* Volume 68, Number 1, January/February, pp. 94-127.

Alesch, Daniel J., Robert Nagy, and Craig Taylor, 2002, "Seeking Criteria for the Natural Hazard Investment Decision," pp. 160-186 in *Acceptable Risk Processes: Lifelines and Natural Processes*, edited by Craig Taylor and Erik VanMarcke, Reston, VA: American Society of Civil Engineers.

American Lifelines Alliance (ALA), 2004, *Guideline for Assessing the Performance of Electric Power Systems in Natural Hazard and Human Threat Events*, www.americanlifelinesalliance.org, April 30.

Apostolakis, George E., 2004, "How Useful Is Quantitative Risk Assessment?," pp 515-520 in *Risk Analysis*, Vol. 24, No. 3.

Applied Technology Council (ATC-40), 1996, *Seismic Evaluation and Retrofit of Concrete Buildings*, California Seismic Safety Commission Report SSC 96-01, Applied Technology Council, Redwood City, California, Nov.

Aschheim, M., 2004, "A pragmatic Approach to PBSD," *International Workshop on Performance-Based Seismic Design: Concepts and Implementation,* Bled, Slovenia, June 28-July 1.

Aschheim, M. A., and E. FR. Black, 2000, "Yield Point Spectra for Seismic Design and Rehabilitation," *Earthquake Spectra*, Vol. 16, No. 2, pp. 317-335.

Atkinson, Gail M. and David M. Boore, 1997, "Some Comparisons Between Recent Ground-Motion Relations," pp. 24-40 in *Seismological Research Letters,* January/February.

Bernstein, Peter, 1996, *Against the Gods: The Remarkable Story of Risk*, New York: John Wiley & Sons, Inc.

Campbell, Kenneth W. And Yousef Bozorgnia, 2002, "Mutually Consistent Near-Source Attenuation Relations for the Horizontal and Vertical Components of PGA and Acceleration Response Spectra," submitted to the *Bulletin of the Seismological Society of America*, January 4, 2002.

Daykin, C. D., T. Pentikainen, and M. Pesonen, 1994, *Practical Risk Theory for Actuaries*, London: Chapman & Hall.

Earthquake Engineering Research Institute (EERI), 2000, *Financial Management of Earthquake Risk*, Oakland, CA: EERI, EERI Endowment Subcommittee on Financial Risk Management.

Efron, Bradley and Robert J. Tibshirani, 1993, *An Introduction to the Bootstrap*, New York: Chapman & Hall.

Federal Emergency Management Agency (FEMA 273), 1997, *NEHRP Guidelines for Seismic Rehabilitation of Buildings*, Washington, D. C., October.

Ferrito, J. M., Stephen Dickenson, Nigel Priestley, Stuart Werner, and Craig Taylor, 1999, *Seismic Criteria for California Marine Oil Terminals*, Port Heuneme, CA: Naval Facilities Engineering Service Center, Technical Report TR-2103-SHR, sponsored by the Marine Facilities Division, California State Lands Commission, May.

Frankel, Arthur D., Mark D. Petersen, Charles S. Mueller, Kathleen M. Haller, Russell L. Wheeler, E. V. Leyendecker, Robert L. Wesson, Stephen C. Harmsen, Chris H. Cramer, David M. Perkins, and Kenneth S. Rukstales, 2002, *Documentation for the 2002 Update of the National Seismic Hazard Maps*, Denver, CO: U. S. Geological Survey, Open-File Report 02-420.

The H. John Heinz III Center for Science, Economics and the Environment, 2000, **The Hidden Costs of Coastal Hazards: Implications for Risk Assessment and Mitigation**, Washington, D. C.: Island Press.

Inel, M., E. Black, M. Aschheim, and D. Abrams, 2000, *Utility Software for Earthquake Engineering, Version 1.0 and Manual*, Urbana, IL: Mid-America Earthquake Center, http://mae.ce.uiuc.edu

Levy, Haim, 1998, *Stochastic Dominance: Investment Decision Making Under Uncertainty*, Boston: Kluwer Academic Publishers.

Levy, Haim and Marshall Sarnat, 1984, *Portfolio and Investment Selection: Theory and Practice*, New Jersey: Prentice Hall International.

Lew, Jacob J., 1999, "1999 Discount Rates for OMB Circular No. A-94," Washington, D. C.: Office of Management and Budget, www2.whitehouse.gov/omb/memoranda/m99-11.html.

Markowitz, H. H., 1959, *Portfolio Selection: Efficient Diversification of Investments*, New York: John Wiley & Sons.

Moore, John L., 1995, "Cost-Benefit Analysis: Issues in Its Use in Regulation," Washington, D. C., Congressional Research Service, The Committee for the National Institute for the Environment, June 28, www.cnie.org/nle/rsk-4.html.

Office of Management and Budget (OMB), 1972, "Discount Rates to be Used in Evaluating Time-Distributed Costs and Benefits," Off ice of Management and Budget (OMB), Executive Office of the Present, Circular No. A-94, revised March 27.

Office of Management and Budget (OMB), 1992, "Benefit-Cost Analysis of Federal Programs: Guidelines and Discounts," Federal Register, vol. 57, No. 218, 53519-53528, www.whitehouse.gov/OMB/circulars/a094/a094.html.

Panel on Seismic Hazard Evaluation, 1996, *Review of Recommendations for probabilistic Seismic Hazard Analysis: Guidance on Uncertainty and Use of Experts*, Washington, D. C.: National Academy Press.

Perkins, David, 2002, "Uncertainty in Probabilistic Hazard Analysis," pp. 19-60 in *Acceptable Risk Processes: Lifelines and Natural Hazards,*, ed. by Craig Taylor and Erik VanMarcke, Reston, VA: American Society of Civil Engineers, Council on Disaster Reduction and Technical Council on Lifeline Earthquake Engineering, Monograph No. 21, March.

Perkins, David and Craig Taylor, 2003, "Earthquake occurrence modeling for evaluating seismic risks to roadway systems," *Advancing Mitigation Technologies and Disaster Response for Lifeline "Systems: Proceedings of the Sixth U. S. National Conference on Lifeline Earthquake Engineering,* ed. by James E. Beavers, Reston, VA: American Society of Civil Engineers, Technical Council on Lifeline Earthquake Engineering Monograph No. 25, pp. 859-867.

Porter, Keith A., James L. Beck, and Rustem V. Shaikhutdinov, 2002, "Sensitivity of Building Loss Estimates to Major Uncertain Variables," Earthquake Spectra, vol 18, Number 4, November, pp. 719-744.

Reasenberg, Paul A., Thomas C. Hanks, and William H. Bakun, 2003, "An Empirical Model for Earthquake Probabilities in the San Francisco Bay Region, California, 2002-2031," BSSA, Vol 93, Number 1, February, pp. 1-13.

Resnick, Michael D., 1987, *Choices: An Introduction to Decision Theory*, Mineapolis, MN: University of Minnesota Press.

Rose, Adam, 2002, "Model Validation in Estimating Higher Order Economic Losses from Natural Hazards," pp. 105-134 in *Acceptable Risk Processes: Lifelines and Natural Hazards*, ed. by Craig Taylor and Erik VanMarcke, Reston, VA: American Society of Civil Engineers, TCLEE Monograph No. 21.

Taylor, Craig E., Stuart D. Werner, and Steve Jakubowski, 2001, "Walkthrough Method for Catastrophe Decision Making," *Natural Hazards Review*, November, pp. 193-202.

Taylor, Craig E. David M. Perkins, and Stuart D. Werner, 2004, *Post-Sampling Variance Reduction for Seismic Risk Analysis of Spatially Distributed Lifeline Networks,* for the

Multidisciplinary Center for Earthquake Engineering, Buffalo, New York, under FHWA Contract DTFH61-98-C-00094, July.

Toro, Gabriel R., Norman A. Abrahamson, and John F. Schneider, 1997, "Model of Strong Ground Motions from Earthquakes in Central and Eastern North America: Best Estimates and Uncertainties," pp. 41-57 in *Seismological Research Letters,* January/February.

VanMarcke, Erik H. and C. Allin Cornell, 1969, *Analysis of Uncertainty in Ground Motion and Structural Response Due to Earthquakes*, Cambridge, MA: the Massachusetts Institute of Technology, R69-24, April.

Werner, Stuart D., Stephen E. Dickenson, and Craig E. Taylor, 1997, "Seismic Risk Reduction at Ports: Case Studies and Acceptable Risk Evaluation," *Journal of Waterway, Port, Coastal, and Ocean Engineering*, pp. 337-346, November/December.

Werner, Stuart D., Craig E. Taylor, James E. Moore III, Jon S. Walton, and Sungbin Cho, 2000, *A Risk-Based Methodology for Assessing the Seismic Performance of Highway Systems*, Buffalo, NY: Multidisciplinary Center for Earthquake Engineering Research, Technical Report MCEER-00-0014, FHWA Contract Number DTFH61-92-C-00016.